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NEWLY DISCOVERED GEOLOGICAL FEATURES AND THEIR POTENTIAL IMPACT ON DARLINGTON AND PICKERING

by

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Report

RÉSUMÉ

De nouvelles données révèlent la présence d'un linéament aéromagnétique nord/nord-est et des modèles linéaires à tendance est/nord-est dans des sédiments récents sur le fond du lac Ontario. Cette bordure magnétique du nom de «Niagara–Pickering» passe pratiquement sous la centrale nucléaire Pickering (8 réacteurs de 1600 MW) et à environ 30 km à l'ouest de la centrale nucléaire Darlington (4 réacteurs de 2800 MW). Des données magnétiques laissent supposer que le linéament magnétique Niagara–Pickering pourrait être un indice de faille et rejoindre le linéament magnétique Akron (Ohio) à laquelle plusieurs tremblements de terre semblent relier. D'autre part, des données géologiques semblent appuyer l'hypothèse d'une faille. Deux tremblements de terre qui se sont produits au 19e siècle dans la péninsule du Niagara, l'un d'intensité V et l'autre d'intensité VI, ont eu lieu très près du linéament magnétique Niagara–Pickering. Les modèles linéaires dans les sédiments au fond du lac pourraient être d'origine tectonique.

Une anomalie de gravité linéaire Bouguer à tendance nord/nord-ouest traverse la partie occidentale du lac Ontario à proximité des centrales nucléaires Darlington et Pickering et s'étend depuis l'État de New York en direction nord/nord-ouest au moins jusqu'à la partie méridionale de la baie Georgienne. Il existe aussi un linéament magnétique parallèle à l'anomalie linéaire Bouguer, qui traverse la bordure magnétique Niagara–Pickering vers le long de la côte orientale de la baie Georgienne. Du lac Simcoe au coin nord-est de la baie Georgienne, une bordure topographique se superpose aux bordures gravitationnelle et magnétique. La bordure topographique pourrait aussi s'étendre en direction sud/sud-est vers l'État de New York. Les relations spatiales des bordures exprimées différemment l'une par rapport à l'autre impliquent que chacune représente une signature différente de la même structure ou zone crustale principale, qui est mieux connue sous le nom de «zone linéaire de la baie Georgienne». Une bande d'épicentres de tremblements de terre à tendance nord/nord-ouest, qui comprend les séismes de Lockport (N.Y.) [d'une magnitude estimée de 5,0] et d'Attica (N.Y.) [d'une magnitude de 5,8], se situe parallèlement juste à l'est de toute la longueur de la baie Georgienne en direction d'Attica (N.Y.). La proximité et le parallélisme de la zone linéaire de la baie Georgienne par rapport à cette bande d'épicentres de séismes impliquent que la zone linéaire de la baie Georgienne pourrait être tectoniquement active.

La zone linéaire de la baie Georgienne et le linéament magnétique Niagara–Pickering semblent se croiser très près de Pickering et à moins de 30 km de Darlington. Ces faits, ajoutés à l'évidence de fortes contraintes horizontales dans la région et l'implication que les deux linéaments pourraient être sismiquement actives, font supposer que plusieurs des éléments nécessaires pour provoquer un tremblement de terre d'une mangitude d'au moins 5,0 à 6,25 existent à proximité de Darlington et de Pickering. Il est donc nécessaire que le linéament magnétique Niagara–Pickering, la zone linéaire de la baie Georgienne et les nouvelles caractéristiques structurales récemment découvertes soient bien évaluées pour déterminer si les tremblements de terre de dimensionnement de Darlington et de Pickering sont exacts.

Table of Contents

	Page
List of Figures	2
List of Tables	2
Abstract	4
A. Introduction	4
B. The Niagara-Pickering Magnetic Lineament	5
C. The Georgian Bay Linear Zone	6
D. Geologically Young Structures in the Western Lake Ontario Area	8
1. Pop-ups	8
a. General Statement	8
b. Age	9
c. The Potential Significance of Pop-ups to Seismic Hazard	9
d. Pop-ups in Western Lake Ontario	10
2. Plumose Structures	10
3. Elongate "Sand Volcanoes"	10
4. Offset Boreholes	10
E. Earthquakes and The Akron (Ohio) Magnetic Boundary	11
F. Comparisons Between the Niagara-Pickering Magnetic Lineament and the Akron Magnetic Boundary	12
G. Implications of Geologically Young Structures, the Niagara-Pickering Magnetic Lineament and the Georgian Bay Linear Zone on Darlington and Pickering	12
H. Summary and Conclusions	13
Selected References	14
APPENDIX 1	18
Investigations	18
APPENDIX 2	19
Table 4 Calculation of Peak Acceleration as a Function of Magnitude & Distance (Hasegawa, Basham & Berry, 1981)	19
APPENDIX 3	20
Table 5 Calculation of Peak Acceleration as a Function of Magnitude & Distance (Boore & Atkinson, 1987)	20

List of Figures

All of the Figures follow APPENDIX 3

Figure 1	The Niagara-Pickering Magnetic Lineament (In Pocket)
Figure 2	The Oshawa Magnetic Lineament (In Pocket)
Figure 3	Isopach map of the Trenton and Black River groups in southwestern Ontario
Figure 4	Earthquakes and the Niagara-Pickering Magnetic Lineament
Figure 5	The Niagara-Pickering Magnetic Lineament and the magnetic signature of the Georgian Bay Linear Zone
Figure 6	The gravity signature of the Georgian Bay Linear Zone and the location of the Attica Earthquake
Figure 7	The topographic expression of the Georgian Bay Linear Zone
Figure 8	The linear distribution of earthquakes and the Georgian Bay Linear Zone
Figure 9	The Niagara-Pickering Magnetic Lineament, the Georgian Bay Linear Zone and the Attica, Timiskaming and Leroy earthquakes
Figure 10	Pop-up at Young's Point, Ontario
Figure 11	Pop-up southwest of Alexandria Bay, New York
Figure 12	Pop-ups in quarries at Niagara Falls, N.Y. and Quebec City
Figure 13	Histogram showing pop-up orientations v. frequency
Figure 14	Stress map of the eastern United States
Figure 15	Crustal stresses in eastern Canada and the adjacent United States
Figure 16	Plumose structures and elongate sand volcanoes(?)
Figure 17	The Akron Magnetic Boundary and associated earthquakes
Figure 18	Compilation of structural elements in southern and eastern Ontario, western Quebec and the adjacent United States
Figure 19	The locations of the Montreal, Timiskaming, Cornwall and Grand Banks earthquakes
Figure 20	Seismic zoning map of Canada

List of Tables

		Page
Table 1	Fracture Orientations in Rocks near the CMBBZ	5

Table 2.	Earthquakes spatially related to the Georgian Bay Linear Zone	7
Table 3	Displaced Boreholes and Stress Trends at the Darlington Site.	11
Table 4	Calculation of Peak Acceleration as a Function of Magnitude & Distance (Hasegawa and others, 1981)	19
Table 5	Calculation of Peak Acceleration as a Function of Magnitude & Distance (Boore and Atkinson, 1987)	20

Newly Discovered Geological Features and Their Potential Impact on Darlington and Pickering

Abstract

Newly available information reveals the presence of a prominent north-northeast oriented aeromagnetic lineament and east-northeast trending, linear patterns in young sediments on the bottom of Lake Ontario. The magnetic lineament, named the Niagara-Pickering Magnetic Lineament, passes practically beneath the Pickering Nuclear Generating Station (8x1600 MW reactors), and about 30 km west of the Darlington Nuclear Generating Station (4x2800 MW reactors). Magnetic data suggest that the Niagara-Pickering Magnetic Lineament may be the signature of a fault and may connect with the Akron Magnetic Boundary in Ohio, with which several earthquakes appear to be associated. Geological data lend support to the fault hypothesis. Two 19th century earthquakes on the Niagara Peninsula, one an intensity V and the other an intensity VI, occurred very close to the Niagara-Pickering Magnetic Lineament. The linear patterns in the lake bottom sediments could be tectonic in origin.

A north-northwest trending linear Bouguer gravity anomaly crosses western Lake Ontario in the vicinity of both the Darlington and Pickering Nuclear Generating Stations and extends from New York State, north-northwestward into at least the southern portion of Georgian Bay. A magnetic lineament parallels the linear Bouguer anomaly in its traverse from the Niagara-Pickering Magnetic Lineament into, and along side the east coast of, Georgian Bay. From Lake Simcoe to the northeastern corner of Georgian Bay, a topographic lineament is superimposed on both the gravity and magnetic lineaments. The topographic lineament may also extend south-southeastward into New York State. The spatial relationships of the differently expressed lineaments to each other implies that each represents a different signature of the same major crustal structure or structural zone, referred to here as the Georgian Bay Linear Zone. A north-northwest trending belt of earthquake epicenters, which includes the Lockport, N.Y. earthquake (est M=5.0) and the Attica, N.Y. earthquake (M=5.8), lies just east of, and parallels, the entire length of Georgian Bay en route to Attica, New York. The proximity and parallelism of the Georgian Bay Linear Zone to this belt of earthquake epicenters implies that the Georgian Bay Linear Zone may be tectonically active.

The Georgian Bay Linear Zone and the Niagara-Pickering Magnetic Lineament appear to intersect very near Pickering and within about 30 km. from Darlington. This, combined with evidence of high horizontal stresses in the area and the implication that both lineaments may be seismically active, suggests that many of the ingredients necessary for an earthquake of at least M=5.0 to M=6.25 exist near both Darlington and Pickering. Therefore, it is necessary that the Niagara-Pickering Magnetic Lineament, the Georgian Bay Linear Zone and the other newly discovered structural features be properly evaluated in order to determine whether or not the current Design Basis Seismic Ground Motions (DBSGM) for Darlington and Pickering are adequate.

A. Introduction

The Design Basis Seismic Ground Motion (DBSGM) for the nuclear generating stations at Darlington and at Pickering ("A" and "B") were determined solely through the assessment of previous earthquakes with no geological, nor any other geophysical, input (Basham, 1975 and Earth Physics Branch, Energy, Mines & Resources, 1980). Since then geophysical maps, showing a north-northwest oriented linear feature with some possibly associated seismic activity, were examined and documented by Wallach (1980, 1981). Within the last $1\frac{1}{2}$ years additional features were identified from airborne magnetic and marine geophysical investigations, respectively conducted in the area of western Lake Ontario by the Geological Survey of Canada and McQuest Marine Research and Development of Burlington, the results of which appear on a recently published total field aeromagnetic map and on side-scan sonar records. During the same time information on the north-northwest trending structure has been augmented by examining the most recently available gravity, magnetic and seismological maps. The evidence accumulated to date indicates the need to conduct, as

soon as possible, a full-scale, fully integrated seismotectonic program relevant to re-evaluating the DBSGM for each of the three nuclear generating stations.

B. The Niagara-Pickering Magnetic Lineament

The total field aeromagnetic map (Figure 1) displays several linear anomalies in western Lake Ontario. The most prominent, herein named the **Niagara-Pickering Magnetic Lineament** (NPML), crosses the lake in a north-northeasterly direction (015°-020°) and extends from at least the Niagara Peninsula, through Pickering, north to the latitude of Lake

Table 1. Fracture Orientations in Rocks near the CMBBZ

Location County Road 503, 6.5 km west of Hwy 35 at Norland, Ontario:
Rock Type Gull River Limestone
Bedding Horizontal

Strike	Dip	Strike	Dip	Strike	Dip
110°	90°	100°	88°	027°	90°
026°	90°	100°	88°	025°	90°
025°	84°	355°	90°	200°	87°
030°	85°	203°	87°	020°	90°
023°	87°	033°	62°	285°	85°

Location County Road 503 in the village of Norland, 1 km west of Hwy 35:
Rock Type Gneissic granite
Foliation 020°-35° and 028°-25°

215°	83°	265°	85°	298°	89°
270°	90°	303°	90°	350°	85°
257°	80°	225°	89°	218°	86°
220°	90°	215°	73°	042°	90°

Simcoe (Figures 1, 3, 5, 9 and 18). Magnetically, the amplitude, wave length, and strike length of the NPML are comparable to those of the Clarendon-Linden Fault (Forsyth and Mohajer, personal communications), which crosses Lake Ontario about 100 km east of the Niagara-Pickering Magnetic Lineament and **is perhaps the longest and oldest active fault in the eastern United States** (Fakundiny and others, 1978). Beneath Lake Ontario, the NPML marks the abrupt and precipitous change from tightly contoured, magnetically higher values on the west to much more broadly contoured, magnetically lower values on the east (Compare Figures 1 & 17). The NPML may be the southern continuation of the linear anomaly recognized by Forsyth (1981) and Forsyth and others (in press) as coinciding with the Central Metasedimentary Belt Boundary Zone (CMBBZ), which marks the western limit of the Central Metasedimentary Belt in the Grenville Province (Wynne-Edwards, 1972).

Forsyth and others (in press), in discussing the CMBBZ, stated that it "appears to truncate (and offset ?) more easterly anomaly trends...". Hanmer (1988) noted that, in the Grenville Province to the north, the CMBBZ is unequivocally a reverse, ductile fault zone which formed approximately 1,060 ma ago. Besides the predominantly ductile deformation, steeply dipping, north-northeast oriented fractures were identified in the gneissic granites, effectively within the CMBBZ near Norland, Ontario, and in the Middle Ordovician, Gull River Limestone to the west. Some of the fractures, which cut the gneissic granites, are filled with granitic dikes and a few others show epidote on the surface. The filled or coated fractures most likely formed during the later stages of the Grenvillian orogeny when temperature-pressure conditions were still elevated, yet were low enough to permit brittle behavior. The age(s) of the uncoated, unfilled fractures is unknown. Orientations of some

fractures, from both the gneissic granites and the Gull River Limestone, are shown in Table 1. The data in this table are not the result of any exhaustive study and may not even be representative of the major fracture sets in the area. They are presented solely to show that in, and adjacent to, the southern part of the exposed Canadian Shield, there are brittle structures oriented parallel to the CMBBZ and to the NPML.

Though recognized on an outcrop scale, the north-northeast fractures imply that similarly oriented, much longer (perhaps regional-scale) brittle fractures also exist. Shadow Lake, a north-trending lake just east of Norland, and Gull Lake, a north-northeast oriented lake north of Norland, both lie within the CMBBZ. To the south, in the Middle Ordovician rocks, the western part of Lake Scugog is situated within a topographic lineament aligned with the NPML (Figure 2). The alignment of the lakes and their relationship to both the NPML and the CMBBZ lend further support to the possible correlation of the two. Moreover, the locations and orientations of these three lakes suggest that the CMBBZ, despite its origin as a ductile fault zone, may currently be the locus of a regional-scale, brittle structure. If so, it could be capable of concentrating stored strain energy consequent upon the application of tectonically-derived stress. This raises the question of whether, or not, the CMBBZ could be seismogenic. However, before any conclusions about its seismogenic potential can be drawn, much more work is required.

In the immediate vicinity of Lake Ontario there have not yet been any direct geological observations of the CMBBZ. However, isopachs of the Trenton and Black River Groups in southwestern Ontario, derived from subsurface geological data (Sanford, 1961), show a distinct linear valley which trends north-northeast (Figure 3) and seems to coincide with the NPML. This valley indicates an elongate thickening of the Trenton-Black River sequence resulting from deposition into a topographic depression which may, or may not, have been tectonically active at the time of sedimentation.

The linearity and the contrasting magnetic properties on opposite sides of the NPML suggest that it may be the signature of a fault. Its location, relative to the characteristics, orientation and location of the CMBBZ, and its magnetic similarity to the seismically active Clarendon-Linden Fault, reinforce this impression.

In 1853 an earthquake of MM intensity V (Smith, 1962) occurred on the Niagara Peninsula near St. Catherines. The epicenter for this event lies on, or very close to, the trace of the NPML (Figure 4). In 1873 a second earthquake, of intensity VI (Smith, 1962), occurred on the Niagara Peninsula and its epicenter is also on, or very close to, the trace of the NPML. If the locations of these earthquakes are reasonably accurate the NPML may be a seismically active structure.

C. The Georgian Bay Linear Zone

An elongate aeromagnetic anomaly in the Precambrian rocks beneath Oshawa was recognized by Wallach in 1981. Herein referred to as the Oshawa Magnetic Lineament, it is marked by a magnetic depression which disrupts the continuity of the generally east-northeast to northeast orientation of the regional magnetic fabric (Figure 2). It is at least 30 km long and extends from beneath Lake Ontario, north-northwestward where it appears to intersect, and be truncated by, the Niagara-Pickering Magnetic Lineament (Figures 2 & 9). The epicenter of an MM III earthquake, which occurred in 1877, is located on this feature.

Magnetic contours near the southeast corner of Lake Simcoe reveal a distinct, broad, northwest oriented fabric which appears to continue further north (Figure 2). This is confirmed in Figure 5, which shows a band of north-northwest trending magnetic lineaments in, and on the north side of, Lake Simcoe. The most prominent of the suite of northwest-trending lineaments passes along the west side of the lake in its extent from just north of the Niagara-Pickering Magnetic Lineament into, and toward the northeast corner of, Georgian Bay, a distance of about 200 km (Figures 5 & 9). The location and orientation of all

of these lineaments, including the Oshawa Magnetic Lineament, suggests that all may be magnetic signatures of a lengthy, north-northwest trending structure or structural zone which stretches from at least the north shore of Lake Ontario well into Georgian Bay.

A north-northwest oriented, linear Bouguer gravity anomaly, which parallels the magnetic lineaments, stretches more than 300 km from New York State, across Lake Ontario, to the southern part of Georgian Bay (Figure 6). At what appears to be its southern end, near Attica, New York, it intersects a second gravity anomaly which is oriented in a north-south direction and signifies the Clarendon-Linden Fault. The intersection marks the location of the 1929, M=5.8 Attica earthquake (Figure 6).

Besides the magnetic and gravity signatures, geologic and topographic features have been identified. The topographic feature, expressed as a lineament, was observed on Landsat imagery and interpreted by Sanford, Thompson and McFall (1985) as one of several major crustal, cratonic, block boundaries tectonically reactivated at least during the earliest Paleozoic. This lineament coincides with the ruler-straight, east coast of Georgian Bay on its north-northwest trajectory from Lake Simcoe to the northeast corner of Georgian Bay, a distance of 200 km (Figure 7). According to Sanford, Thompson and McFall, it may also continue from Lake Simcoe, south-southeastward into New York State.

The geological feature was detected by subsurface exploration undertaken by Sanford (1961) and is expressed on his isopach map which is reproduced in Figure 3 of this report. It is a linear zone of thickened Trenton-Black River sediments, similar to that spatially associated with the NPML. It lies just east of Toronto, parallels all of the aforementioned features and extends from beneath Lake Ontario northwest toward Lake Simcoe (Figure 3). Like the zone associated with the NPML, this feature is interpreted as resulting from deposition in a linear trough which may, or may not, have been tectonically active at the time of sedimentation.

Each of the four differently expressed, parallel lineaments (topographic, aeromagnetic, gravimetric and geologic) occurs within the same general geographical area. Furthermore, all

Table 2. Earthquakes Spatially Related to the Georgian Bay Linear Zone

Date	Latitude	Longitude	Magnitude	Location
1852/12/15	43.30°	78.20°	3.0	New York
1857/10/23	43.20°	78.60°	5.0	New York
1877/05/02	43.90°	78.85°	3.0	Ontario
1887/02/19	45.35°	80.00°	3.1	Ontario
1887/03/19	45.35°	80.00°	2.4	Ontario
1907/01/25	44.10°	79.10°	3.7	Ontario
1929/08/12	42.87°	78.35°	5.8	New York
1965/04/01	46.00°	80.50°	3.4	Ontario
1965/02/19	44.62°	79.42°	2.0	Ontario
1965/07/16	43.04°	78.08°	3.1	New York
1969/08/13	43.30°	78.22°	2.5	New York
1975/10/08	43.52°	78.49°	2.0	L. Ontario
1986/07/16	42.99°	78.23°	2.3	New York
1987/12/20	43.11°	78.43°	2.4	New York

From the Geological Survey of Canada

are practically superimposed on one another, are parallel and, except for the isopachous lineament, are proximal to the east coast of Georgian Bay. This relationship suggests that all four are signatures of a major crustal structure, or structural zone, as proposed by Sanford,

Thompson and McFall. Because all, but one, occur within Georgian Bay the structure or structural zone is herein named the **Georgian Bay Linear Zone** (GBLZ).

Epicenters of at least four low-magnitude earthquakes lie on, and define, a line which extends north-northwestward from western New York State to near the Grenville Front, a distance of approximately 400 km (Figure 8). Four others are ≤9 km and an additional three, including the 1857 Lockport (N.Y.) earthquake (est. M=5.0) and the 1929 Attica earthquake (M=5.8), are ≤15 km from this line. In all eleven earthquakes, five of which are in Ontario and two of which would be classified as moderate, are located no further than 15 km from this line. Besides being close to the aforementioned line, the Lockport and Attica earthquakes, themselves, define a line parallel to it and both are situated **within** the gravimetric zone of the GBLZ (Figure 9). Thus, rather than elucidating a simple line, the eleven earthquakes probably outline a zone, or belt, as do the gravity and magnetic components of the GBLZ. As a result of the distribution of earthquakes in New York State it is suggested that the zone might be about 40 km wide (Figure 8) and would include at least fourteen (Table 2), and possibly as many as sixteen, seismic events.

The zone of earthquakes trends north-northwest, parallels the east side of Georgian Bay and passes between Darlington and Pickering. It is also parallel to, and virtually coincident with, the spatially related, linear topographic, aeromagnetic and gravimetric features which are all believed to be different expressions of the Georgian Bay Linear Zone (Figure 9). It is acknowledged that the locations of the pre-instrumented earthquakes may be in error by as much as 50 km, and that even the locations of the instrumented events may also be imprecise. It is also noted that the definition of the earthquake belt, including its width and the number of earthquakes contained therein, is subject to interpretation. Nonetheless, there is an assemblage of earthquakes outlining a linear zone, or band, which is spatially related and parallel to all of the different expressions of the Georgian Bay Linear Zone. This must be more than mere coincidence, making it difficult to ignore the distinct possibility that the Georgian Bay Linear Zone is seismically active.

D. Geologically Young Structures in the Western Lake Ontario Area

1. Pop-ups

a. General Statement

Pop-ups develop at the surface in response to high horizontal compressive stress. In order for them to form there is a need for decoupling, thus the presence of horizontal planes of weakness, whether due to compositional variations or closely spaced fractures in otherwise massive rocks, is a prerequisite. If planes of weakness do not exist, or are steeply dipping, in which case they effectively do not exist, pop-ups will not form even if stress conditions are favorable.

Pop-ups have been identified in a broad belt which extends in a generally northeast direction from north-central Kentucky (Simmons, 1967), through Ohio (Weston Geophysical, 1986), southern and eastern Ontario, western and northern New York State and southern Quebec, to the Miramichi area in New Brunswick. In glaciated areas where the sedimentary cover is thin to non-existent, pop-ups have been recognized in open fields (e.g. Dames & Moore, 1974; McFall, personal communication) (Figures 10 & 11); they have also been documented on quarry floors (e.g. Saull and Williams, 1974; Adams, 1982; McKay, 1986; Wallach and Chagnon, in preparation) (Figure 12).

Pop-ups generally trend northwest, though they display other orientations as well (Figure 13). At some locations, such as in the McFarland Quarry near Ottawa (Adams, 1982), and in the Ciment St-Laurent Quarry, just outside of Quebec City (Wallach and Chagnon, in preparation), both northwest and northeast to east-northeast pop-ups coexist. Elsewhere, for

example in the Niagara Stone Quarry near Niagara Falls, New York, the pop-ups trend north-northeast.

b. Age

The age of pop-ups occurring in open fields cannot be established unequivocally, although there are criteria for determining age relative to glaciation. If glacially-polished or striated surfaces are deformed by pop-ups, the pop-ups are post-glacial. Examples have been recognized in the 1000 Islands region of northern New York State (Dames & Moore, 1974). Where pop-ups disturb overlying sediments, as in Salt Creek near Toronto (White and others, 1973), they are likely to be younger than, at least, the onset of sedimentation. However, care is required with this interpretation because if the sediments thin across the hinge, differential compaction across an existing pop-up is indicated. If, on the other hand, the deformed layers maintain a uniform thickness across the pop-up, or deformation is expressed as faults, fractures or, perhaps, convolutions in the overlying material, the pop-up would post-date the sedimentation. Strictly speaking unlayered sediments, by themselves, would not provide a unique solution.

Pop-ups that rise above the adjacent rock surface, even without the presence of striated or polished surfaces, are generally considered to have formed subsequent to the last glaciation, which terminated in southern Ontario about 12,000 years ago. This interpretation is logical, but should also be regarded with caution because high fluid pressures could be generated at the base of an ice sheet in which case the ice, and its tools, could literally float over a pre-existing pop-up without eroding it. However, the issue may be resolved by examining the edges of the bedding-extension fracture intersection along the axis of the structure. If the edges are sharp and angular the pop-up, particularly one formed in limestone, is likely to be a very young structure. This is because limestone, with or without acid rain, is a soluble rock and given enough time the sharp edges will be rounded by dissolution. An example of such a case occurs at Young's Point, Ontario, just north of Peterborough. There pop-ups occur in an open field (Figure 10) in which the essentially flat-lying, otherwise undeformed limestone exposes solution-widened, nearly vertical fractures. The lines of intersection between the solution-widened fracture surfaces and the bedding are rounded and smooth, whereas the intersection between the extension fracture, along the axis of the pop-up, and the bedding surface is angular and still rather sharp. These pop-ups are most likely post-glacial and may even be, at most, only a few hundred years old.

In quarries pop-ups form following excavation of the overlying rock, thus they are obviously young (Figure 12). Many cases of this phenomenon have been documented by quarry foremen and superintendents as, for example, at the McFarland Quarry near Ottawa, the Cornwall Gravel Quarry just north of Cornwall, Ontario and the Niagara Stone Quarry in Niagara Falls, New York.

c. The Potential Significance of Pop-ups to Seismic Hazard

Pop-ups have been recognized in areas in which several of the largest earthquakes in eastern North America have occurred. These include the 1732, estimated M_bLg=5.6-6.0, Montreal earthquake (Leblanc, 1981), the 1929, M=5.8 Attica earthquake (Ontario Hydro, 1969; 1974; 1978), the 1944, M=5.9 Cornwall-Massena earthquake (Smith, 1966), the 1981, M_b=5.2 Sharpsburg, Kentucky earthquake (Mauk and others, 1982), the 1982, M_b=5.7 Miramichi earthquake (Burke, 1984), and the 1986, M_b=5.0 Leroy, Ohio earthquake (Nicholson and others, 1988).

The current data base on pop-ups is no doubt incomplete. Nonetheless it can be seen that, despite a variety of orientations, pop-ups most commonly trend approximately northwest (White and others, 1982) (See also Figure 13) which is generally at right angles to the trend of the ambient greatest principal horizontal compressive stress in eastern North America (Figures 14 & 15).

The general orientation and mechanism of formation of pop-ups, relative to the contemporary stress field, along with the demonstrable post-glacial age for many, point to the existence of pop-ups as generally reliable indicators of neotectonic activity. The occurrence and rejuvenation of pop-ups on quarry floors indicates that others are forming at the present time. Since pop-ups have been identified in the vicinity of at least moderate earthquakes (M=5.0 to M=5.9), their presence in areas presently considered aseismic may be an indicator of areas that had been subjected to pre-historic, moderate to large earthquakes and/or are likely to be so affected. In any case, in estimating the seismic potential of an area, pop-ups should not be simply, a priori, ignored.

d. Pop-ups in Western Lake Ontario

In 1987 a swarm of pop-ups, which cut through glaciolacustrine sediments estimated to be on the order of 12,000 years old, was discovered on the lake floor in the western end of Lake Ontario, off Toronto Island (Thomas and MacMillan, personal communications). They may also pierce younger lacustrine sediments as well, suggesting that they may have formed following the retreat of the last glaciation, but how much later is not yet known. However, it is yet to be determined whether the lake-bottom sediments were deposited on pre-existing structures or whether the pop-ups developed subsequent to sedimentation. Nonetheless, their presence in western Lake Ontario suggests tectonic activity in that area. Interestingly, an earthquake (M=3.3) occurred in the vicinity of these pop-ups in July, 1987.

2. Plumose Structures

Plumose structures have been recently identified in young sediments on the bottom of Lake Ontario near Burlington (Thomas and MacMillan, personal communications). They appear as long, thin lines from which delicate wisps of material branch (Figure 16). These structures trend 060°-070°, parallel to both the major stress direction and a prominent fracture trend seen in the Paleozoic bedrock onshore. The origin of these structures is not known. Their presence, however, in very young lake-bottom sediments and their parallelism to both the greatest principal stress and a prominent bedrock fracture trend suggests the possibility that they may represent the upward propagation of fractures in response to the contemporary stress field. Fader (1989, in preparation) has observed the same phenomenon in Passamaquoddy Bay, between southwestern New Brunswick and the state of Maine, and noted that "the distribution of the plumose structures indicated that they occur close to the major faults recognized on land including the Oak Bay Fault." Based on this, and the presence of "eyed" pockmarks, Fader suggested that the Oak Bay Fault may be active.

3. Elongate "Sand Volcanoes"

An aligned series of elongate pods generally parallel, and are proximal to, the plumose structures (Figure 16), though one of the plumose structures is approximately orthogonal to the rest and cuts across the pods. These pods are darker in tone than the adjacent silty sediments and are thought to represent coarser grained material (Thomas, personal communication). Like the plumose structures, they are parallel to a major fracture trend and the greatest principal compressive stress. Their origin, too, is unknown, but their characteristics lead to the suggestion that they may represent fracture-controlled expulsions of sand similar to sand volcanoes. If they are sand volcanoes, they may have been seismically induced, as in the Charlevoix area (Chagnon, and others, 1988) or in the New Madrid, Missouri Seismic Zone (Obermeier, 1985).

4. Offset Boreholes

Offset boreholes, recognized in several areas, are clearly young features which have been interpreted as neotectonic indicators. Block and others (1979) recognized that pre-split boreholes in southeastern Connecticut displayed a reverse sense of motion, with the displaced block actually having moved updip. Bell (1985) documented the same

phenomenon at eight localities in the Rocky Mountains of Alberta and inferred that the boreholes were offset as a consequence of tectonic stresses. Offset boreholes have also been

Table 3. Displaced Boreholes and Stress Trends at the Darlington Site.

Direction of Displacement	Amount of Displacement
230°	1.91 cm
220°	1.27 cm
234°	1.91 cm
230°	11.43 cm
235°	13.97 cm

Average Direction of Displacement 230° (050°)

Stress Orientations	Nature of Test	Depth of Test (m)
070°	Hydraulic Fracturing	74.7
073°	Hydraulic Fracturing	101.5
060°	Hydraulic Fracturing	143.6
077°	Hydraulic Fracturing	184.0
032°	Hydraulic Fracturing	207.4
074°	Overcoring	21.6
056°	Overcoring	35.4
055°	Overcoring	53.9

Average Orientation (Hydraulic Fracturing) 062° (242°)

Average Orientation (Overcoring) 053° (233°)

Stress data from Haimson and Lee (1980)

observed in the Darlington excavation. There, the boreholes were displaced in a generally southwest direction (Table 3), or oblique to the nearly east-west trending, long dimension of the excavation. The displacement, a consequence of slip along horizontal bedding, was also nearly parallel to the orientation of the maximum horizontal compressive stress determined in the Middle Ordovician limestone by Haimson and Lee (1980) (Table 3). Since the displacement was oblique to, rather than into, the excavation and the sense of movement was subparallel to the direction of greatest horizontal compressive stress, it appears unlikely that any mechanism other than the release of tectonically-induced, stored strain energy was responsible for the offset boreholes at Darlington.

E. Earthquakes and The Akron (Ohio) Magnetic Boundary

An earthquake of magnitude 5.0, intensity VI (Holt and others, 1988), occurred January 31, 1986 at Leroy, Ohio, about 17 km. from the Perry Nuclear Power Plant owned by Cleveland Electric Illuminating Co. At the site of the nuclear power plant this earthquake generated a peak ground acceleration of 0.18-0.20g (Klimkiewicz, 1988, oral communication), just slightly greater than the 0.15g used in the design of the plant which sustained no damage. The acceleration at the site was also 2.25 to 7.0 times the peak accelerations for which the units at Darlington and Pickering are designed respectively.

The epicenter of the Leroy earthquake lies on a magnetic lineament which trends about 040° and is about 5 km west of a prominent linear magnetic anomaly (Figure 17), referred to by Weston Geophysical (1986), as the Akron Magnetic Boundary. The Akron Magnetic Boundary (AMB) is at least 50 km long, trends north-northeast and is spatially related to at least six earthquakes, with location uncertainties not exceeding 16 km (Seeber, 1987). From the aeromagnetic maps presented in the report by Weston Geophysical it appears as if the lineament, on which the Leroy earthquake is located, might actually be the western edge of, or at least part of a zone which includes, the AMB.

The focal mechanism of the Leroy earthquake was inferred to be strike-slip with the preferred nodal plane steeply dipping, north-northeast trending and parallel to the AMB (Weston Geophysical, 1986). The epicentral location and the parallelism of one of the nodal planes to the aeromagnetic anomaly suggest that the Leroy earthquake may be genetically related to the linear aeromagnetic anomaly west of the AMB. However, if that anomaly is part of the AMB and/or the dip of the linear surface represented by the AMB is to the west, then the Leroy earthquake may be genetically related to the AMB itself.

A right-lateral strike-slip mechanism was also determined for a small earthquake which occurred south of Lake Ontario, near Fulton, New York, though dip slip faulting on an east-southeast striking plane is equally valid (Quittmeyer, and others, 1988). In either case, the fault plane solutions for that earthquake as well as for the Leroy earthquake are consistent with the generally northeast orientation of the greatest principal horizontal stress which exists, both at depth and at the surface, across all of eastern North America (Figures 14 & 15).

F. Comparisons Between the Niagara-Pickering Magnetic Lineament and the Akron Magnetic Boundary

The Niagara-Pickering Magnetic Lineament and the Akron Magnetic Boundary are linear anomalies having similar orientations and magnetic characteristics (Compare Figures 1 & 17). Both abruptly separate a magnetically positive area characterized by tightly spaced contours, on the west, from a magnetically negative area marked by much more widely spaced contours on the east. In addition both trend generally north-northeast. According to the compilation made by Forsyth and others (in press), the Akron Magnetic Boundary curves towards the northeast in northern Ohio and appears to head towards the NPML (Figure 18). The two lineaments may actually actually connect.

G. Implications of Geologically Young Structures, the Niagara-Pickering Magnetic Lineament and the Georgian Bay Linear Zone on Darlington and Pickering

The presence of pop-ups, plumose structures and elongate, presumably coarser-grained sediments (which may be sand volcanoes) in geologically young sediments on the bottom of western Lake Ontario, suggest that these structures may have formed relatively recently in response to the current, ambient stress field. Earthquake epicenters, distributed in a zone which is parallel to, and overlaps the various signatures of, the GBLZ, imply that the GBLZ may be an active fault zone. The same inference, regarding a potentially active fault, may also be valid for the Niagara-Pickering Magnetic Lineament, at least on the Niagara Peninsula. Collectively, or individually, these features suggest that the western Lake Ontario region is tectonically active and may even become the site of a moderate to large earthquake ($M \geq 5.0$).

The M_b 5.0 Leroy earthquake may be genetically related to the Akron Magnetic Boundary (AMB). If so, similarities between the NPML and the AMB, the possibility that the two may connect, and indications of tectonic and seismic activity in the western Lake Ontario area all add support to the suspicion that a similar-sized earthquake in the vicinity of both Darlington and Pickering could be considered to be a credible event.

Several large and moderate earthquakes in eastern North America have occurred at the junction of major lineaments. These include the Montreal (est. M=5.6-6.0), Grand Banks

(M=7.2) Timiskaming (M=6.25), Attica (M=5.8) and Cornwall-Massena earthquakes (M=5.9) (Figures 6 & 19). Thus, if the NPML and the GBLZ are seismically active faults and intersect, the potential exists for an event **even larger** than the Leroy earthquake. From the magnitudes of Attica and Timiskaming earthquakes, it appears that an earthquake of **at least** M=5.8 to M=6.25 would not be unreasonable though, based on the short documentation history of eastern North American earthquakes, a larger magnitude earthquake cannot be ruled out.

The seismic zoning map (Figure 20), prepared as a basis for establishing the National Building Code of Canada, indicates "anticipated" peak accelerations of between 4%g and 8%g along the north shore of Lake Ontario. The Design Basis Seismic Ground Motion (DBSGM) for Darlington is 8%g, for Pickering "A" it is 3%g and for Pickering "B" it is 5%g. (The DBSGM is actually expressed as a complex function, but reference to peak acceleration is useful for purposes of comparison.) From the equation of Hasegawa and others (1981) a magnitude 5.8 earthquake, at a *hypocentral* distance of ≤30 km, is estimated to be capable of producing a peak acceleration of ≥15%g, whereas a magnitude 6.25 earthquake, at a hypocentral distance of ≤30 km is estimated to be capable of producing a peak acceleration of ≥27%g (Appendix 2). According to the equation of Boore and Atkinson (1987) the same magnitude earthquakes at the same *epicentral* distances indicated above would produce respective peak accelerations of ≥13%g and ≥19%g (Appendix 3). For the larger earthquakes the Boore and Atkinson equation (BA) indicates much lower peak accelerations than the equation of Hasegawa and others (HBB). Despite the differences between the two, given the conditions shown above both would predict peak accelerations substantially in excess of the DBSGM's for all three nuclear stations. However, it is even conceivable that the values from both may be underestimated, at least for near-field earthquakes. For example, the HBB equation indicates a peak acceleration of just above 10%g from a magnitude 5.0 earthquake at a distance of 17 km and the BA equation suggests about 12%g, yet the M_b 5.0 Leroy earthquake generated a peak ground acceleration of 18-20%g at that distance (Klimkiewicz, 1988, oral communication).[1]

H. Summary and Conclusions

The Niagara-Pickering Magnetic Lineament (NPML) may be the signature of a major fault and the Georgian Bay Linear Zone (GBLZ) has several characteristics suggesting that it could be seismically active. Moreover, the two features appear to intersect near both Pickering and Darlington. The occurrence of several moderate to large earthquakes at linear intersections, combined with the characteristics of the NPML and the GBLZ, must not be ignored. Rather, they need to be taken ***as warnings*** that the potential for a moderate to large earthquake, capable of generating accelerations much greater than the DBSGM for each of the nuclear units, would appear to exist near both nuclear generating station sites. The presence of both high horizontal stresses and neotectonic structures in the region enveloping Darlington and Pickering, and documentation of moderate to large-scale seismicity all around western Lake Ontario (Figure 9), add credibilty to this warning.

The possibility that one, and perhaps both, of the major linear features discussed in this report could be seismically active and pass virtually under the Pickering site is of particular concern because even a relatively small earthquake in such a location could create accelerations substantially in excess of the DBSGM (Appendices 2 & 3). It is imperative that seismotectonic conditions in the region encompassing Darlington and Pickering be known as thoroughly as possible. Consequently, the aforementioned features, and the region in which they occur, require a substantial program of seismic monitoring and geological and geophysical investigations to try to determine conclusively whether they, or any other structures, are seismically active and capable of generating peak accelerations considerably

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[1]-Hasegawa (personal communication) stated that the HBB equation is based on estimates from the best data available at the time, but that the data sample itself was inadequate. He cautioned further that the equation may not be applicable within hypocentral distances of about 25-30 km.

greater than the DBSGM's for Darlington and Pickering. It is no longer prudent merely to speculate.

Examples of the kinds of initial activities needed are shown in Appendix 1. The need for further work would be determined by the results of the initial investigations.

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APPENDIX 1

Investigations:

1. Measure seismic sub-bottom profiles along traverses oriented in an approximately east-west direction in Lake Ontario in order to cross the trends of the Niagara-Pickering Magnetic Lineament (NPML) and the Georgian Bay Linear Zone (GBLZ) at as great an angle as possible. A minimum of 10 traverses, each long enough to take possible gentle dips across the NPML and the GBLZ into account, would be required.

Reason: To try to determine whether or not there are topographic expressions (surface rupture) of the NPML and the GBLZ in the young, lake-bottom sediments and, if so, whether layer thicknesses are essentially constant or thin across the ridges. If there are ridges which deform the unconsolidated sediments (the youngest geological strata in the area), and the sediments thin across the top, the ridge would have pre-dated sedimentation and the structure may or may not be active. If layering thickness is more or less constant across a ridge and the sediments are deformed, the structures would have to be considered geologically active. This, in turn, means that there is the potential for a significant earthquake near the generating stations. The absence of surface rupture provides no assurance that the NPML and GBLZ are not active faults. (For example the Miramichi, New Brunswick earthquakes of 1982-1983, M_b=5.7, are not known to have produced surface rupture). However, the efforts undertaken would indicate clearly that all that could be done in attempting to estimata seismic hazard, as accurately as possible, was done. That is not currently the case.

2. Conduct land-based seismic reflection and refraction traverses across the NPML, etc., and the GBLZ, north of Lake Ontario, both across terrain underlain by Precambrian and Paleozoic rocks. As for the marine-based surveys, each traverse should be long enough to take possible gentle dips across the NPML and the GBLZ into account.

Reason: To try to determine the nature of the two linear features and whether or not there are topographic expressions of each.

3. Evaluate deformation in all sand and gravel pits, particularly across or near both the NPML (including the CMBBZ and the linear aeromagnetic anomalies addressed by Forsyth) and the GBLZ, to determine whether or not the deformation is or is not of tectonic origin.

Reason: The sediments in these pits are glacial or post-glacial. Thus, they are young enough so that if they have been deformed tectonically the deformation would be considered neotectonic and should therefore be factored into seismic hazard assessments.

4. Undertake seismic monitoring along both the NNE-trending Niagara-Pickering Magnetic Lineament and the NNW-trending Georgian Bay Linear Zone.

Reason: Since the largest earthquakes in eastern North America commonly occur at the junction of major lineaments, and these two features appear to intersect, it is necessary to determine whether or not there is any microseismic activity along either, or both, of these features.

At least six seismic stations should be placed along each of these features for if there is any seismic activity in the area, it will be far easier to determine, precisely, whether or not the activity is associated with either, or both, of them. Any indication of seismic activity, no matter how small, must serve as a signal that a more thorough knowledge of seismological and geological conditions is required in order to ascertain whether or not there is a reasonable likelihood that the DBSGM for each generating station may be exceeded.

APPENDIX 2

Table 4 Peak Acceleration as a Function of Magnitude & Distance (HBB)

Magnitude	Dist. (km)	Acceleration (%g)	Magnitude	Dist. (km)	Acceleration (%g)
5.00	100	1.45%	5.00	40	3.99%
5.50	100	2.79%	5.50	40	7.63%
5.70	100	3.61%	5.70	40	9.90%
5.80	100	4.12%	5.80	40	11.28%
6.00	100	5.34%	6.00	40	14.62%
6.25	100	7.39%	6.25	40	20.24%
6.50	100	10.22%	6.50	40	28.01%
7.00	100	19.58%	7.00	40	53.66%
5.00	80	1.86%	5.00	30	5.47%
5.50	80	3.56%	5.50	30	10.48%
5.70	80	4.62%	5.70	30	13.59%
5.80	80	5.26%	5.80	30	15.47%
6.00	80	6.82%	6.00	30	20.07%
6.25	80	9.44%	6.25	30	27.77%
6.50	80	13.07%	6.50	30	38.44%
7.00	80	25.03%	7.00	30	73.63%
5.00	60	2.55%	5.00	25	6.68%
5.50	60	4.89%	5.50	25	12.80%
5.70	60	6.34%	5.70	25	16.60%
5.80	60	7.22%	5.80	25	18.91%
6.00	60	9.36%	6.00	25	24.52%
6.25	60	12.96%	6.25	25	33.94%
6.50	60	17.93%	6.50	25	46.97%
7.00	60	34.35%	7.00	25	89.98%
5.00	50	3.12%	5.00	20	8.54%
5.50	50	5.97%	5.50	20	16.36%
5.70	50	7.75%	5.70	20	21.22%
5.80	50	8.82%	5.80	20	24.17%
6.00	50	11.44%	6.00	20	31.35%
6.25	50	15.83%	6.25	20	43.38%
6.50	50	21.91%	6.50	20	60.04%
7.00	50	41.98%	7.00	20	115.02%

Accelerations calculated using the formula $a(cm/sec^2)=3.4(e^{1.3M})(R^{-1.1})$, where a=acceleration in cm/sec^2, M=magnitude and R=hypocentral distance in km. (From Hasegawa, Basham and Berry, 1981.)

APPENDIX 3

Table 5 Peak Acceleration as a Function of Magnitude & Distance (B&A)

Magnitude	Dist. (km)	Acceleration (%g)	Magnitude	Dist. (km)	Acceleration (%g)
5.00	100	0.79%	5.00	40	4.01%
5.50	100	1.47%	5.50	40	6.67%
5.70	100	1.88%	5.70	40	8.11%
5.80	100	2.13%	5.80	40	8.93%
6.00	100	2.71%	6.00	40	10.81%
6.25	100	3.64%	6.25	40	13.64%
6.50	100	4.88%	6.50	40	17.10%
7.00	100	8.64%	7.00	40	26.41%
5.00	80	1.25%	5.00	30	6.02%
5.50	80	2.25%	5.50	30	9.81%
5.70	80	2.82%	5.70	30	11.84%
5.80	80	3.16%	5.80	30	12.99%
6.00	80	3.96%	6.00	30	15.58%
6.25	80	5.21%	6.25	30	19.45%
6.50	80	6.83%	6.50	30	24.12%
7.00	80	11.55%	7.00	30	36.41%
5.00	60	2.11%	5.00	25	7.67%
5.50	60	3.65%	5.50	25	12.37%
5.70	60	4.51%	5.70	25	14.87%
5.80	60	5.01%	5.80	25	16.27%
6.00	60	6.16%	6.00	25	19.44%
6.25	60	7.95%	6.25	25	24.13%
6.50	60	10.19%	6.50	25	29.77%
7.00	60	16.46%	7.00	25	44.43%
5.00	50	2.85%	5.00	20	10.17%
5.50	50	4.83%	5.50	20	16.24%
5.70	50	5.93%	5.70	20	19.44%
5.80	50	6.56%	5.80	20	21.24%
6.00	50	8.00%	6.00	20	25.27%
6.25	50	10.20%	6.25	20	31.20%
6.50	50	12.93%	6.50	20	38.28%
7.00	50	20.43%	7.00	20	56.48%

Log $A=C_0+C_1r-\text{Log } r$; where r=epicentral distance in km, M=moment magnitude and $A=cm/sec^2$

$C_0 = 3.763+(3.354\times10^{-1})(M-6)-(2.473\times10^{-2})(M-6)^2$
$C_1=-3.885\times10^{(-3)}+(1.842\times10^{-3})(M-6)-(9.169\times10^{-5})(M-6)^2$
(From Boore and Atkinson, 1987.)

Figure 3. Isopach map of the Trenton and Black River Groups in southwestern Ontario. Note the two linear valleys, south and southeast of Lake Simcoe, each of which indicates deposition of sediments into a linear trough. They appear to coincide, respectively, with the Georgian Bay Linear Zone (GBLZ, marked by the open arrows) and the Niagara-Pickering Magnetic Lineament (NPML, marked by solid arrows).

(Modified after Sanford, 1961)

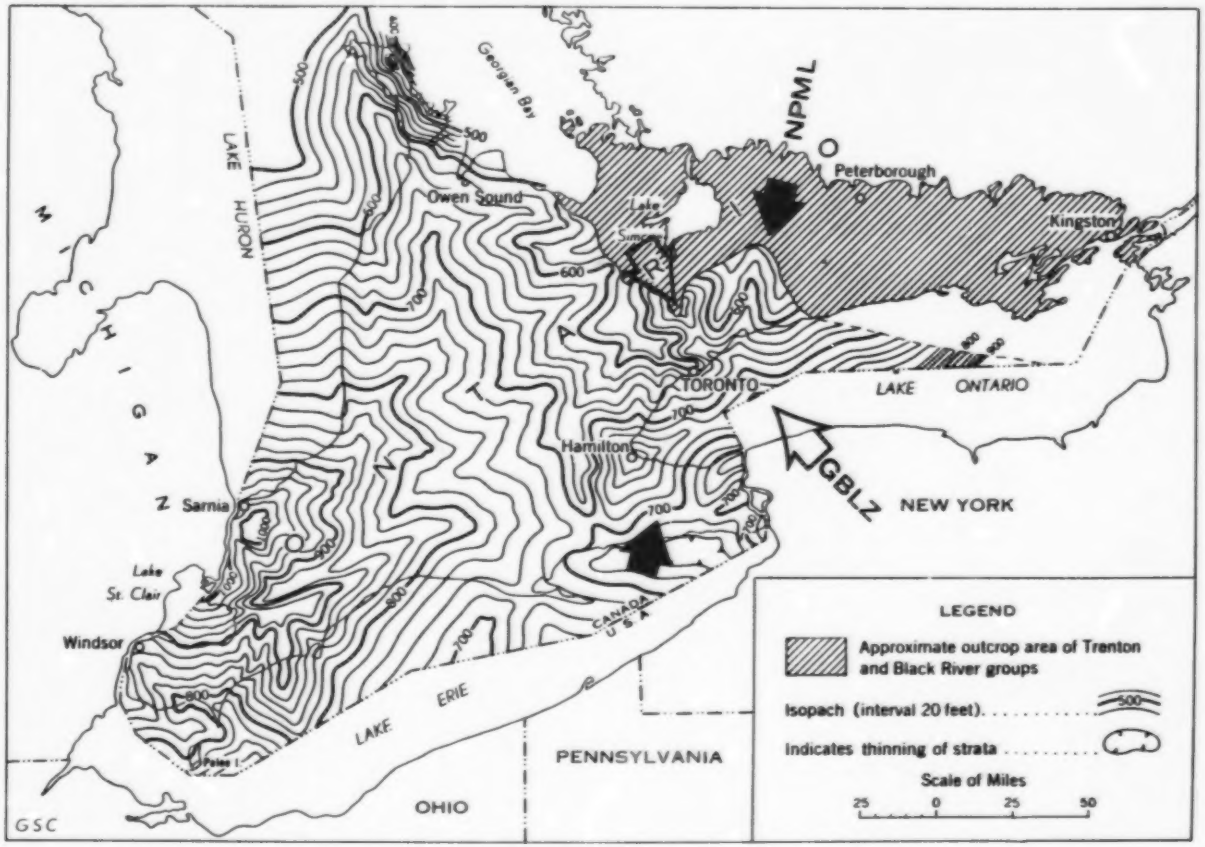
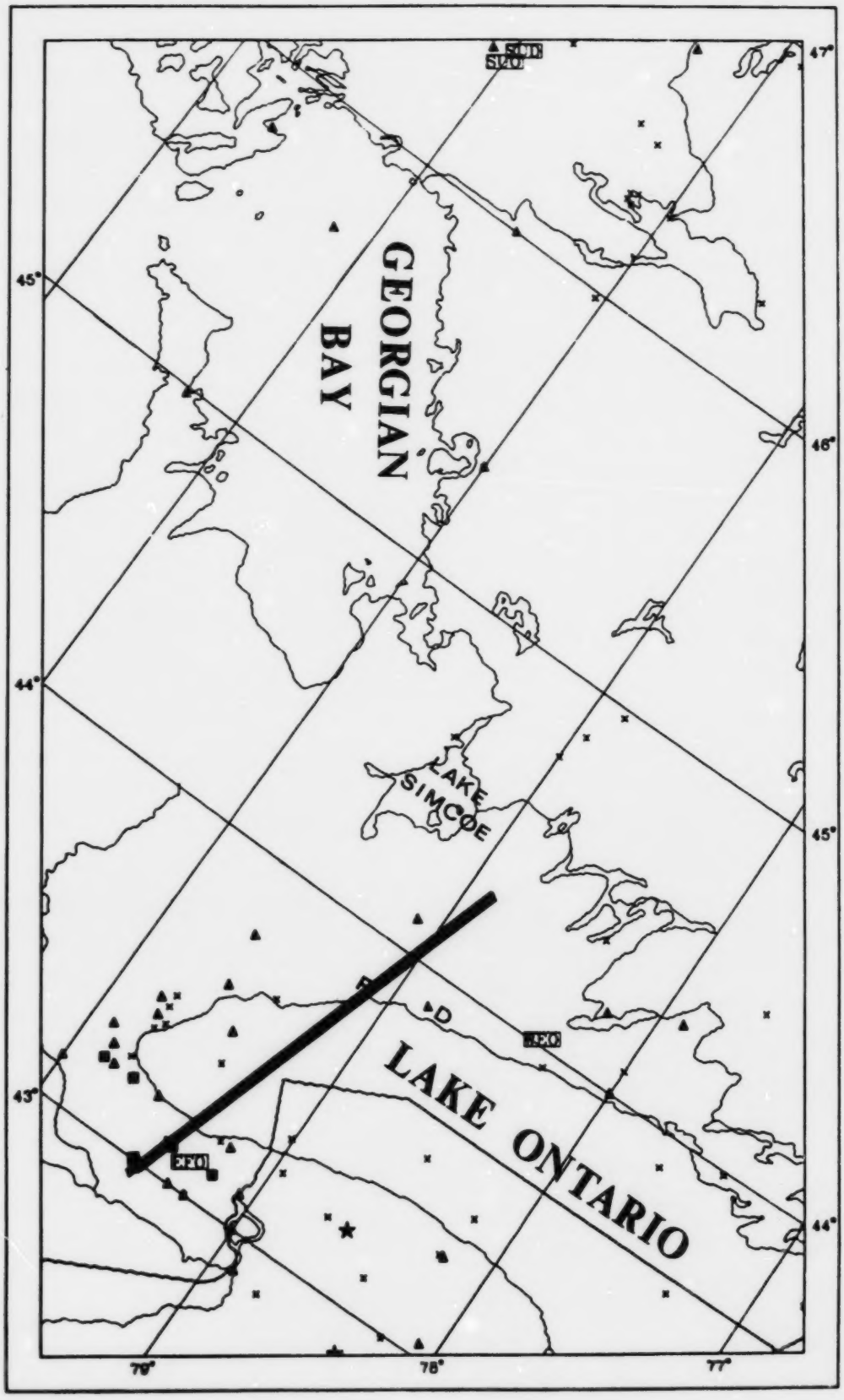

Georgian Bay
LAKE HURON
MICHIGAN
Owen Sound
Lake Simcoe
NPML
Peterborough
Kingston
TORONTO
LAKE ONTARIO
Hamilton
GBLZ
NEW YORK
Sarnia
Lake St. Clair
Windsor
CANADA
U.S.A.
LAKE ERIE
PENNSYLVANIA
OHIO
GSC
LEGEND
Approximate outcrop area of Trenton and Black River groups
Isopach (interval 20 feet)
Indicates thinning of strata
Scale of Miles
25 0 25 50

Figure 4. Earthquakes and the Niagara-Pickering Magnetic Lineament (red line).

D -- Site of the Darlington Nuclear Generating Station

P -- Site of the Pickering Nuclear Generating Station

(Seismic data and base map from the Geological Survey of Canada)



LEGEND

M<3	·
M≥3	▲
M≥4	■
M≥5	★
M≥6	⊛

Figure 5. Total field aeromagnetic map showing the Niagara-Pickering Magnetic Lineament (solid arrows) and the magnetic signature of the Georgian Bay Linear Zone (open arrows). Note how the broad, generally magnetic high, to the left of the solid arrows, curves toward the southwest in passing from north to south. (Compare with Figure 18)

Dx - Site of the Darlington Nuclear Generating Station

P -- Site of the Pickering Nuclear Generating Station

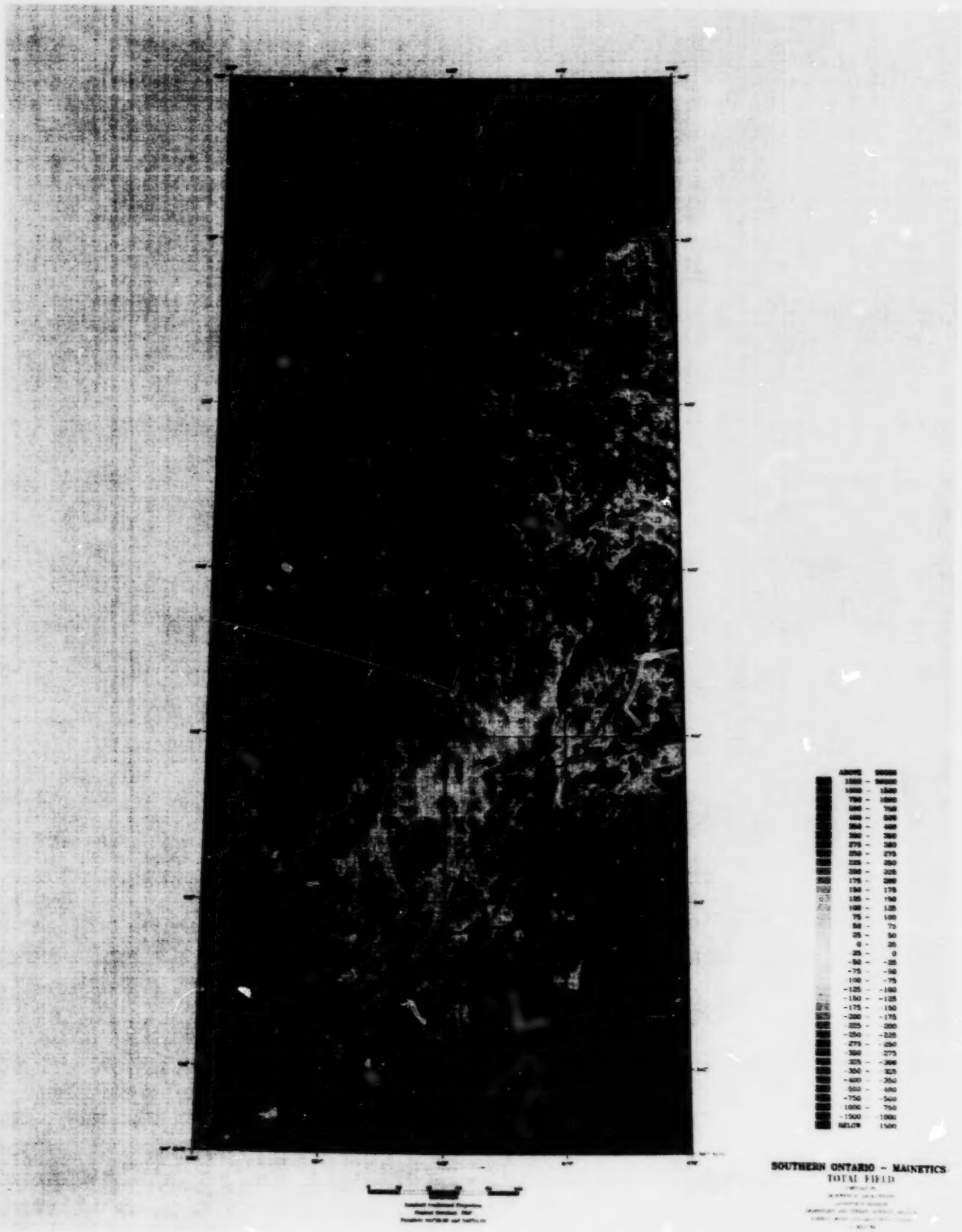

SOUTHERN ONTARIO - MAGNETICS
TOTAL FIELD

Figure 6. Bouguer gravity map showing the gravity signature of the Georgian Bay Linear Zone (arrows).

D -- Site of the Darlington Nuclear Generating Station

P -- Site of the Pickering Nuclear Generating Station

A -- Location of the Attica earthquake of 1929. Note its occurrence at the intersection of two linear gravity anomalies, the first representing the Georgian Bay Linear Zone, the second representing the Clarendon-Linden Fault

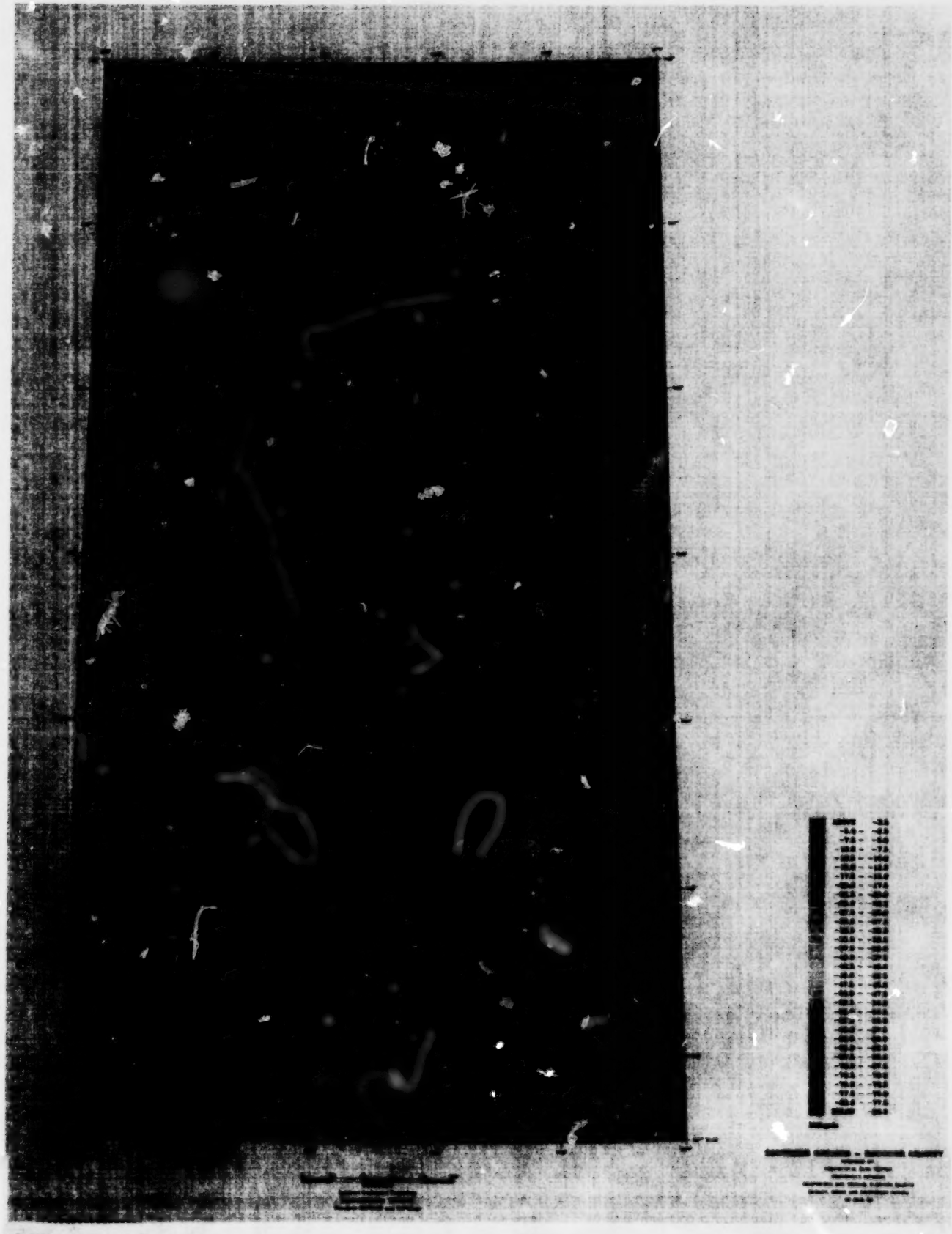


Figure 7. Block boundaries and fractures identified from LANDSAT imagery. The topographic expression of the Georgian Bay Linear Zone is indicated by GBLZ.

(From Sanford, Thompson and McFall, 1985)

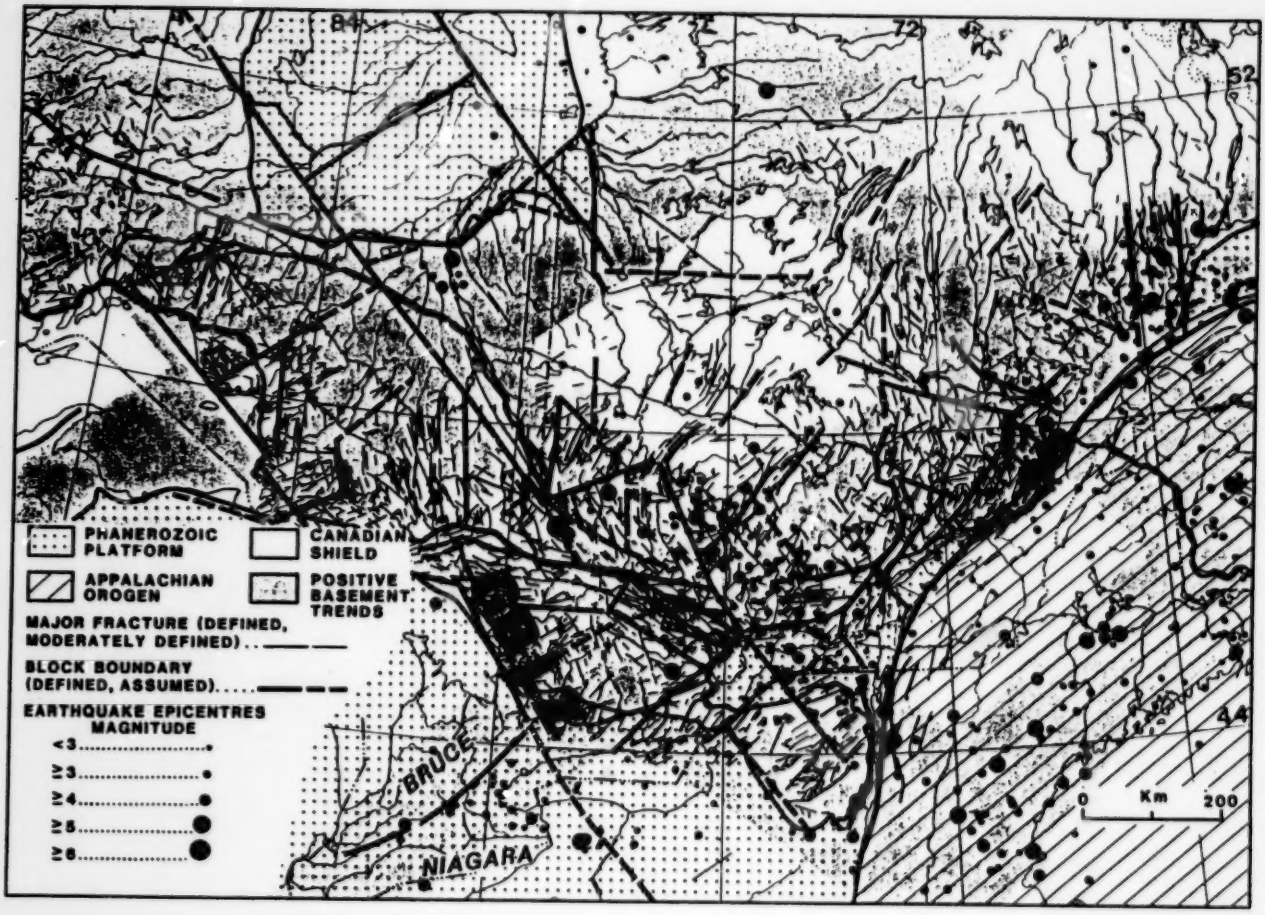
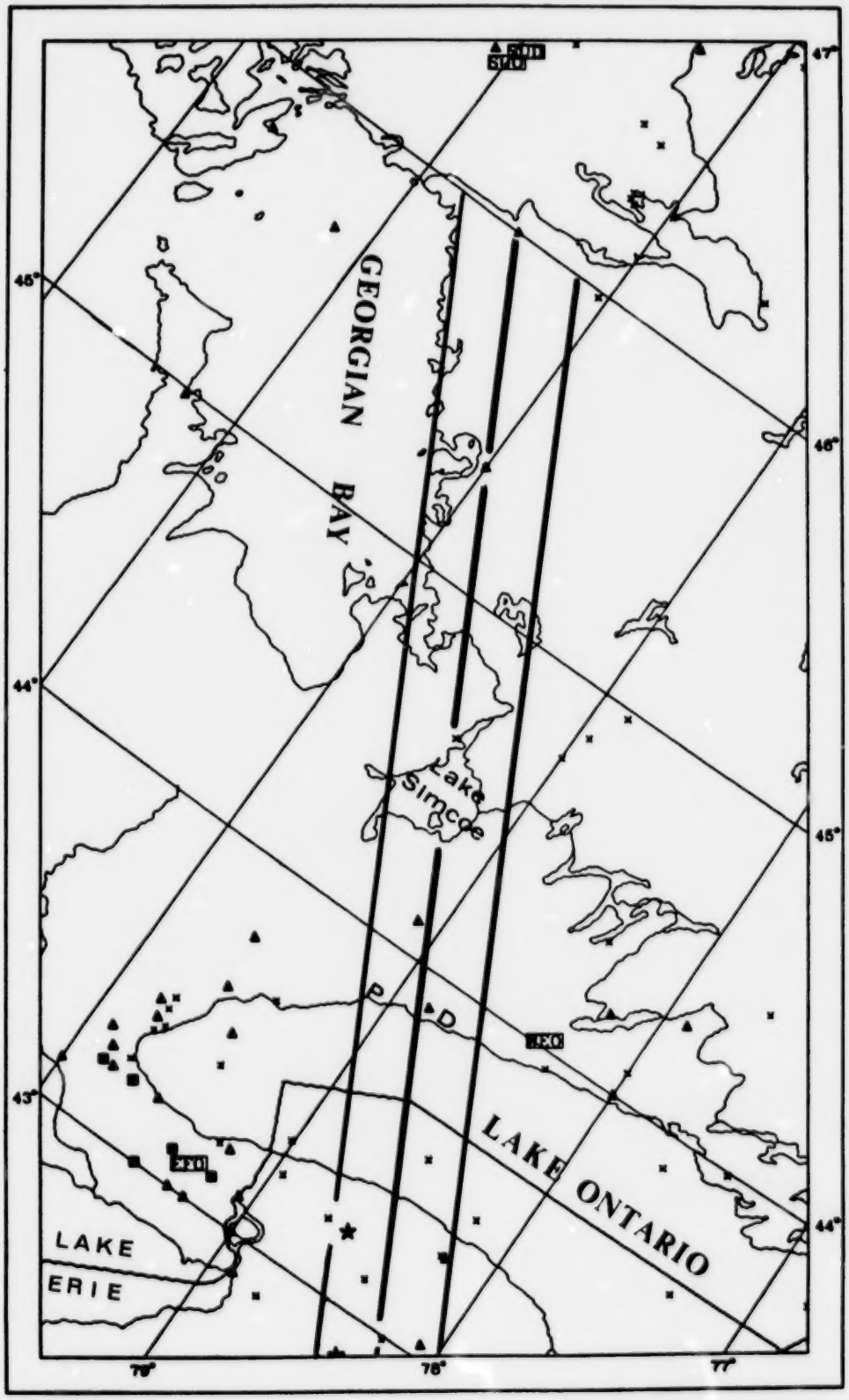

84
72
52
44
PHANEROZOIC PLATFORM
CANADIAN SHIELD
APPALACHIAN OROGEN
POSITIVE BASEMENT TRENDS
MAJOR FRACTURE (DEFINED, MODERATELY DEFINED)
BLOCK BOUNDARY (DEFINED, ASSUMED)
EARTHQUAKE EPICENTRES MAGNITUDE
<3
≥3
≥4
≥5
≥6
BRUCE
NIAGARA
0 Km 200

Figure 8. Earthquakes in the western Lake Ontario-Georgian Bay area, at least fourteen of which occur within a zone extending from, and along, the east side of Georgian Bay into western New York State. The center line is about 400 km long and is ≤15 km from eleven of the epicenters, five of which are in Ontario. The lines on each side of the center line delimit the zone. The bar at the bottom of the figure represents a distance of 200 km.

D - Site of the Darlington Nuclear Generating Station

P - Site of the Pickering Nuclear Generating Station

(Seismic data and base map from the Geological Survey of Canada)



LEGEND

M<3	·
M≥3	▲
M≥4	■
M≥5	★
M≥6	⊛

Figure 9. Relationship of the Niagara-Pickering Magnetic Lineament (black line) to the different signatures of the Georgian Bay Linear Zone (green lines for the linear gravity zone, red lines for the magnetic lineaments, and blue for the linear array of earthquakes). The earthquakes define a zone, rather than a line (see Figure 8). However, for presentation purposes, only the line in the center of the zone is shown. The short red line represents the Oshawa Magnetic Lineament. Locations of the Attica (A), Leroy (Le), Lockport (Lo) and Timiskaming (T) earthquakes are also shown.

D -- Site of the Darlington Nuclear Generating Station

P -- Site of the Pickering Nuclear Generating Station

(Seismic data and base map from the Geological Survey of Canada)

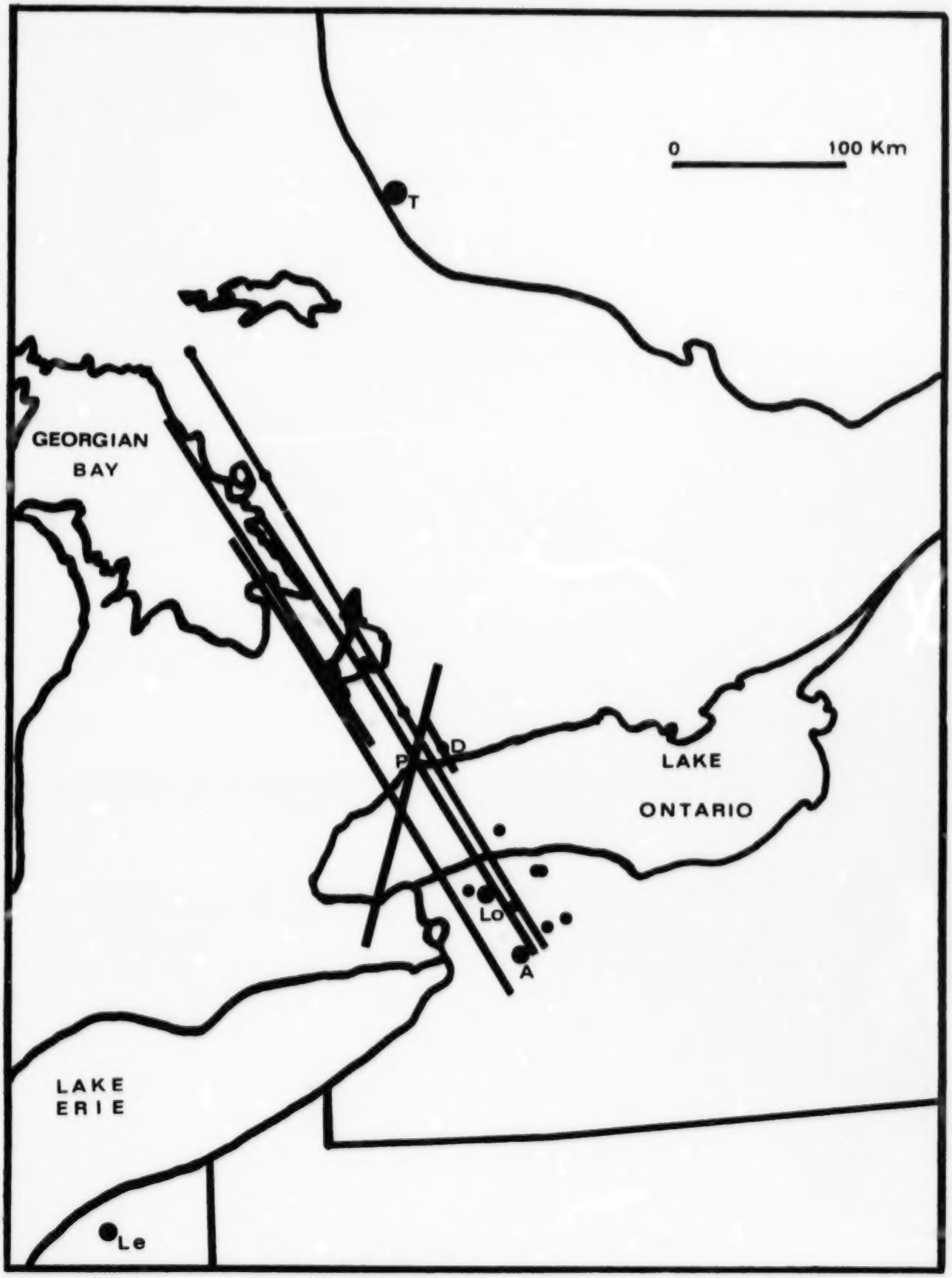

0
100 Km
T
GEORGIAN
BAY
LAKE
ONTARIO
LAKE
ERIE
Le

Figure 10. Pop-up in limestone at Young's Point, Ontario. Top photo shows the axial trend of the structure. Bottom photo shows the angular intersection between the bedding (dipping to the left) and the axial fracture (in the center of the photo).

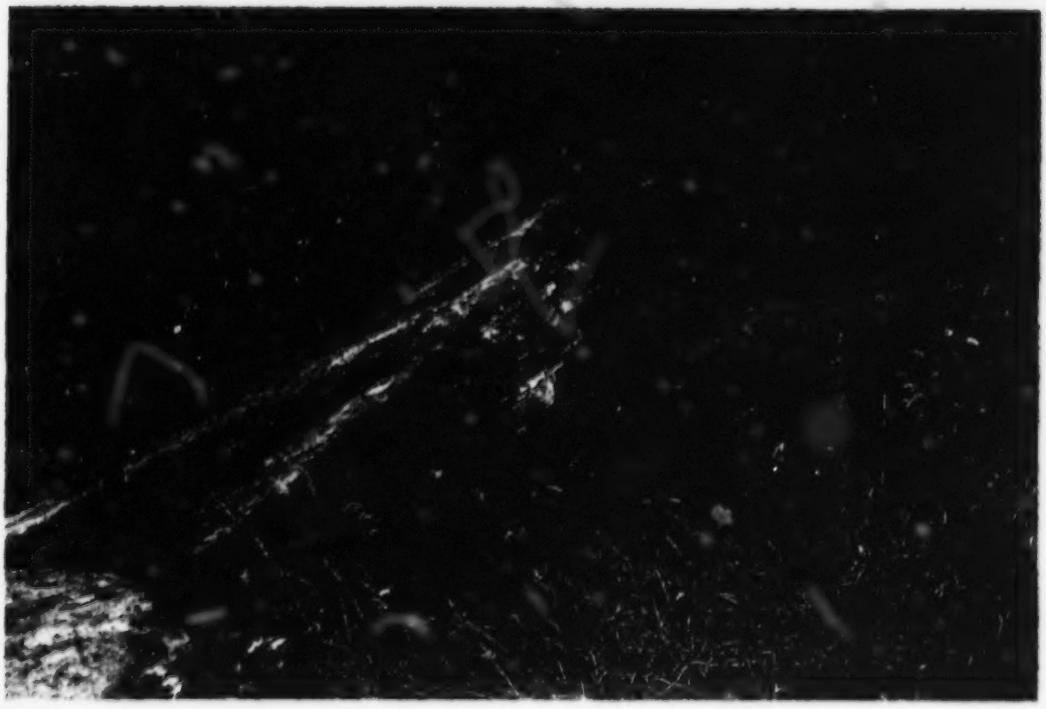


Figure 11. Pop-up in sandstone southwest of Alexandria Bay in the 1000 Islands Region of New York State.

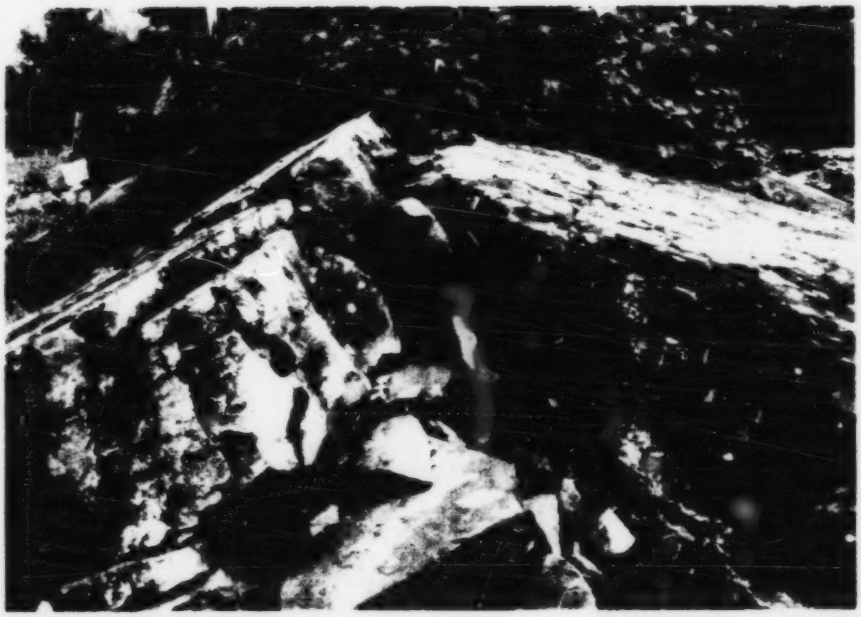
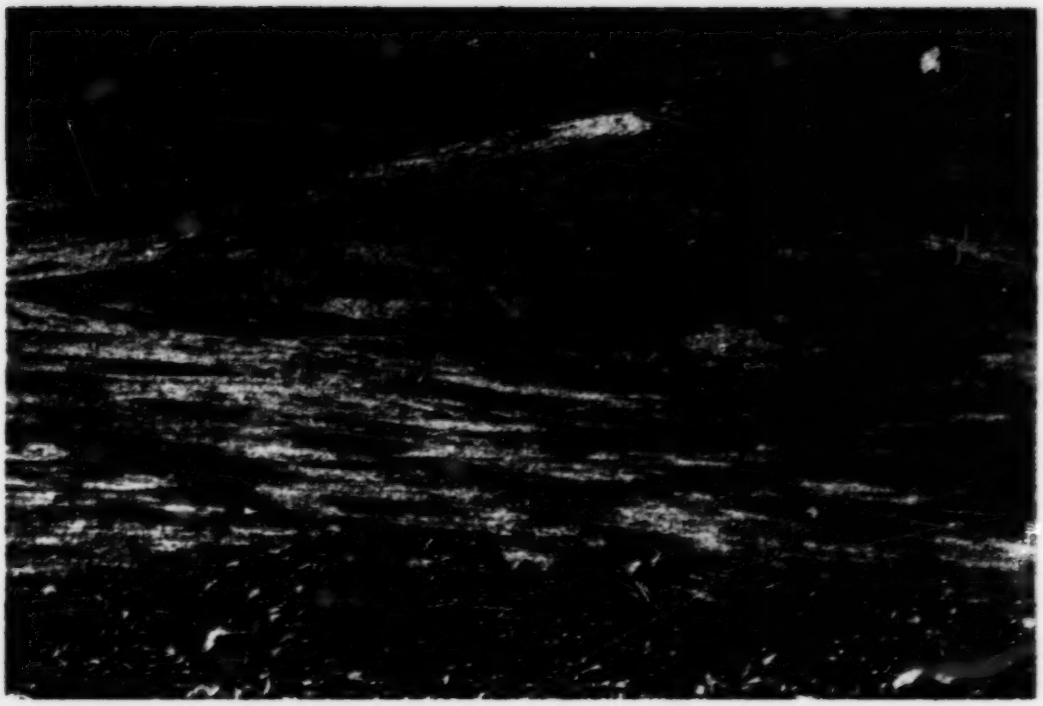


Figure 12. Pop-ups in quarries. The upper photo is from a dolomite quarry near Niagara Falls, New York and the lower photo is from a limestone quarry near Quebec City.



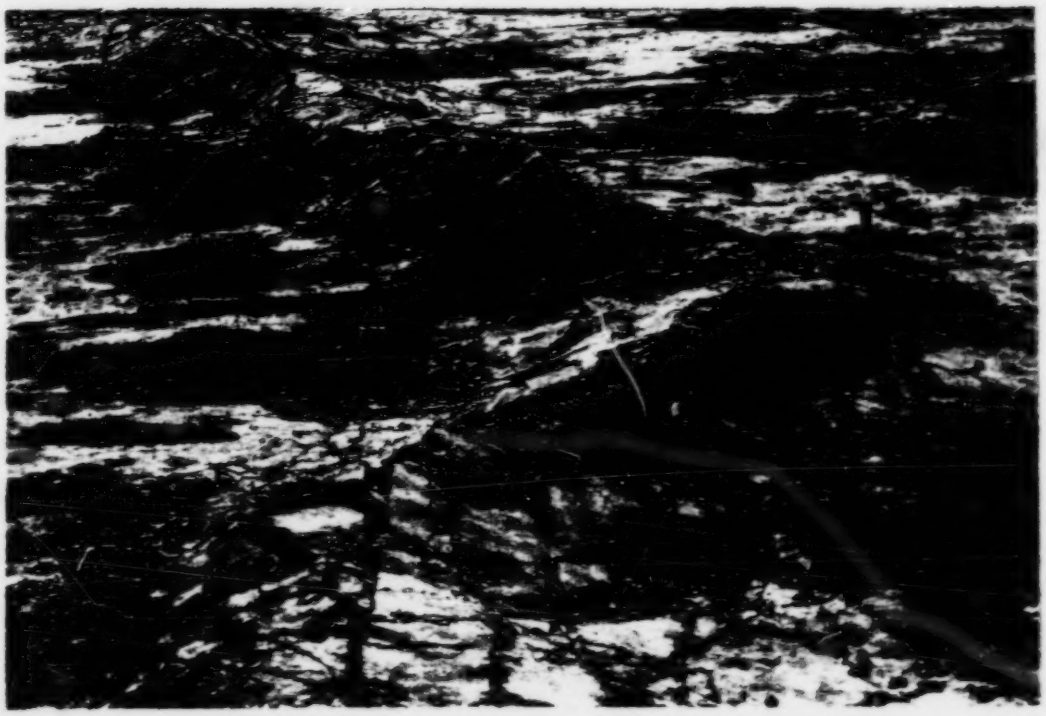


Figure 13. Histogram showing pop-up orientations v. frequency. Each orientation along the abscissa is actually the median value which represents a spread of approximately ±10°. Hence the orientation 010° includes trends ranging from 001° to 020°, the orientation 030° includes trends ranging from 021° to 040°, etc.

Data sources include:

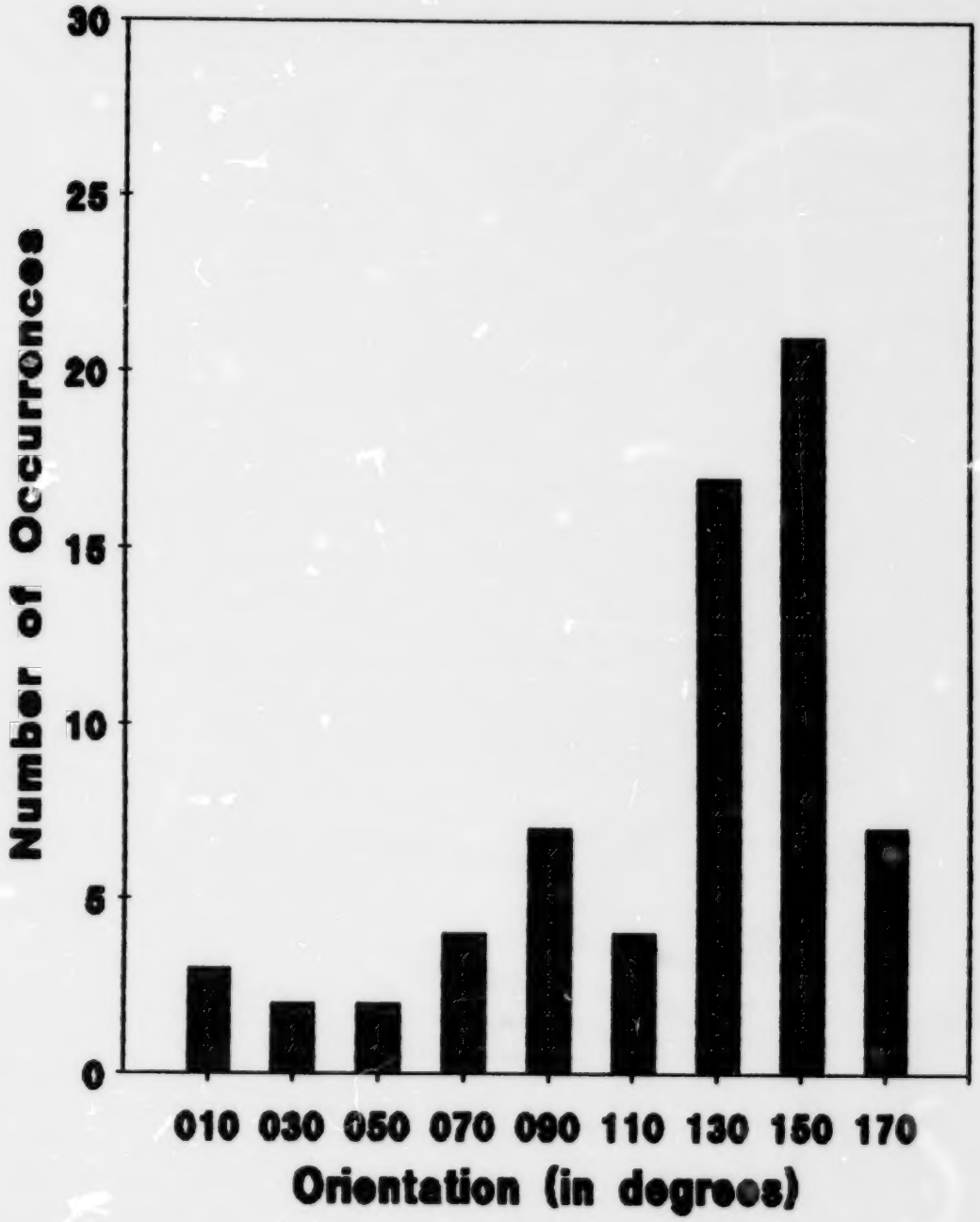
Adams, 1982
Dames and Moore, 1974
McFall, personal communication
McKay, 1986
Saull and Williams, 1974
White and Russell, 1982
Williams, Corkery and Lorek, 1985

Figure 14. Stress map of the eastern United States.

(From Zoback, 1987)

POP-UP ORIENTATIONS

N=67



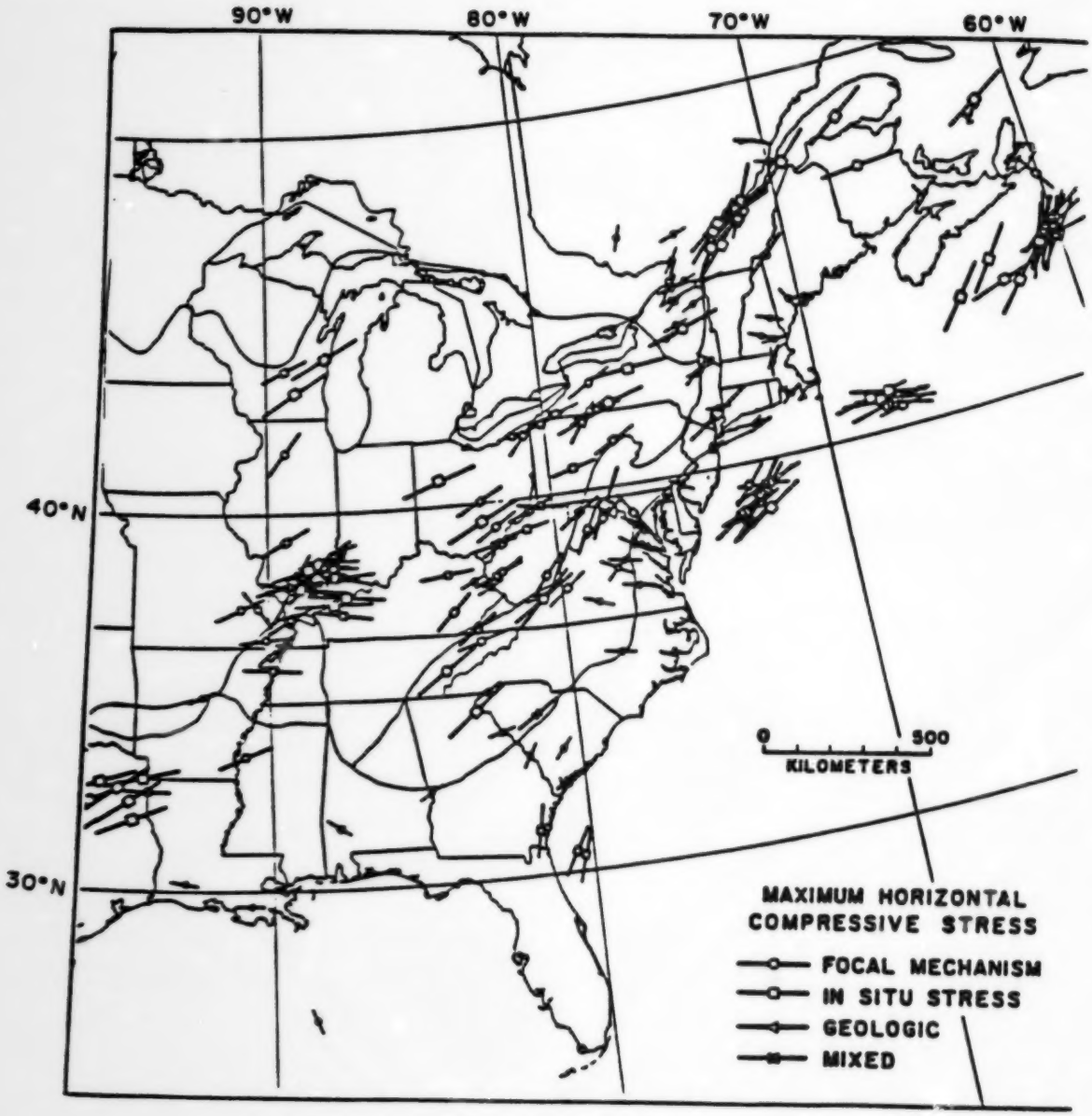

90°W
80°W
70°W
60°W
40°N
30°N
0
500
KILOMETERS
MAXIMUM HORIZONTAL
COMPRESSIVE STRESS
FOCAL MECHANISM
IN SITU STRESS
GEOLOGIC
MIXED

Figure 14. Stress map of the eastern United States.

(From Zoback, 1987)

Figure 15. Stress orientations in eastern Canada and the adjacent United States.

(From Adams and Basham, 1987)

Figure 16. Side scan sonar record showing plumose structures and elongate sand volcanoes (?) (dark spots) in the sediments beneath Lake Ontario near Burlington and Oakville.

(Courtesy of the Canadian Aviation Safety Board)

Figure 17. Residual total field magnetic map showing the Akron Magnetic Boundary (shaded zone) and epicenters of the most prominent, known earthquakes in northeastern Ohio. PNPP is the Perry Nuclear Power Plant. The 1986 event is the M_b 5.0, Leroy earthquake. Note that the main earthquakes appear to be spatially associated with the Akron Magnetic Boundary.

(From Seeber, 1987)

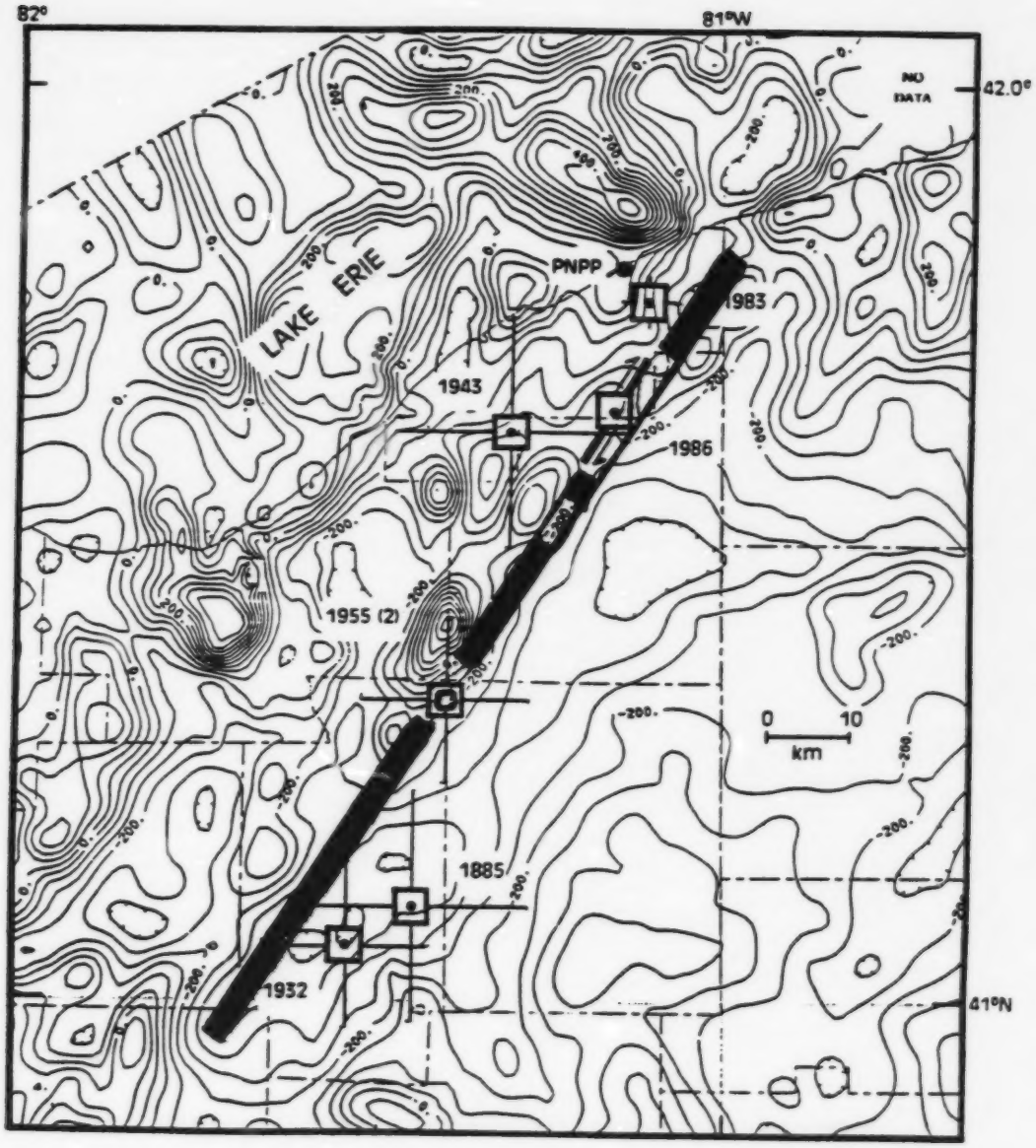

82°
81°W
42.0°
41°N
NO DATA
LAKE ERIE
PNPP
1983
1943
1986
1955 (2)
1885
1932
0 10
km

Figure 18. Compilation of structural elements in southern and eastern Ontario, western Quebec and the adjacent United States. Open arrows denote the Niagara-Pickering Magnetic Lineament, which may coincide with the Central Metasedimentary Belt Boundary Zone (CMBBZ). Note that the Akron Magnetic Boundary and the Niagara-Pickering Magnetic Lineament appear to curve towards one another.

T marks the location of the 1935 Timiskaming earthquake at the intersection of the Grenville Front Tectonic Zone and the Ottawa River.

(Modified after Forsyth and others, in press)

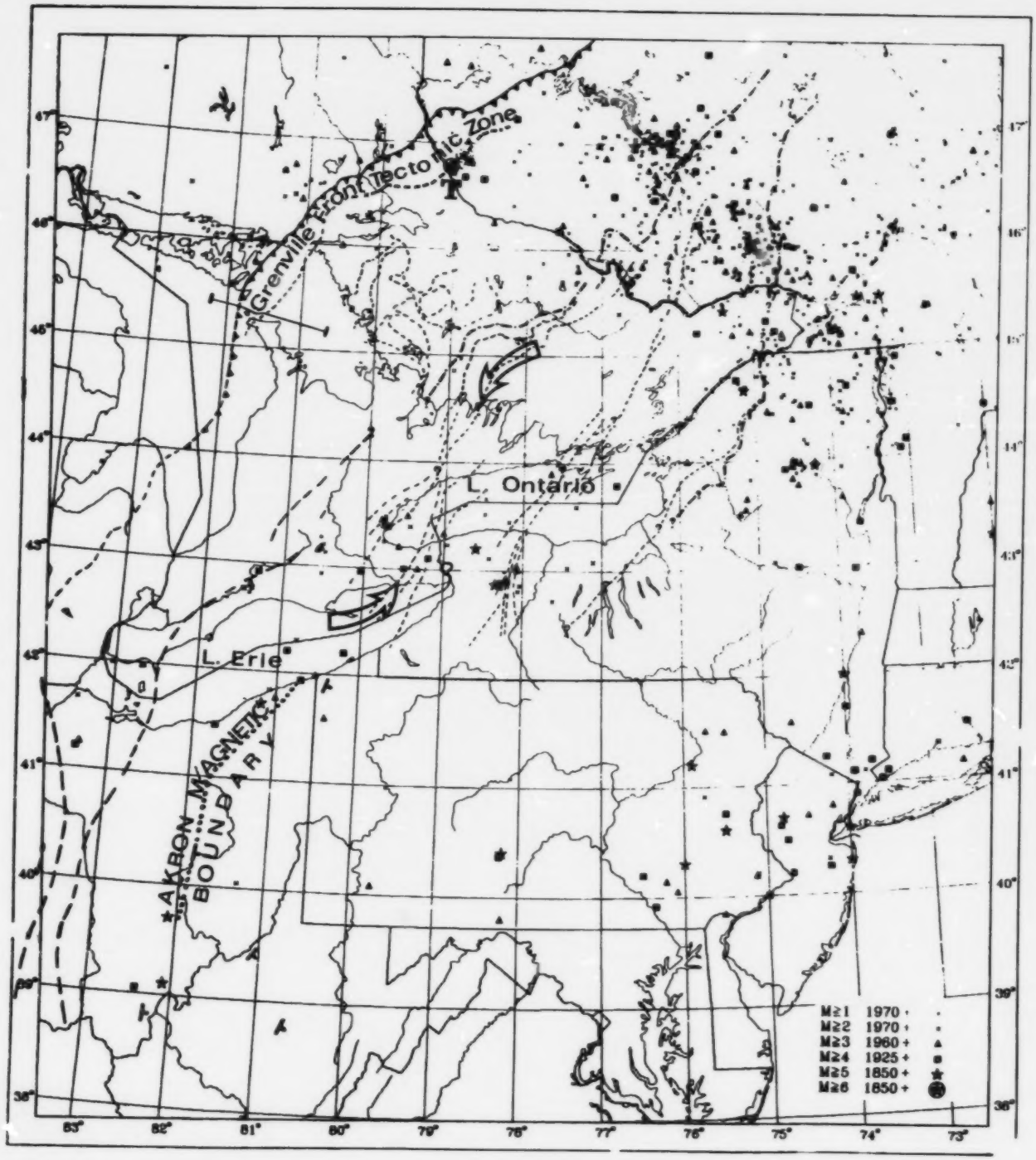

Grenville Front Tectonic Zone
L. Ontario
L. Erie
AKRON MAGNETIC BOUNDARY
M≥1 1970+
M≥2 1970+
M≥3 1960+
M≥4 1925+
M≥5 1850+
M≥6 1850+
47°
46°
45°
44°
43°
42°
41°
40°
39°
38°
85°
82°
81°
80°
79°
78°
77°
76°
75°
74°
73°

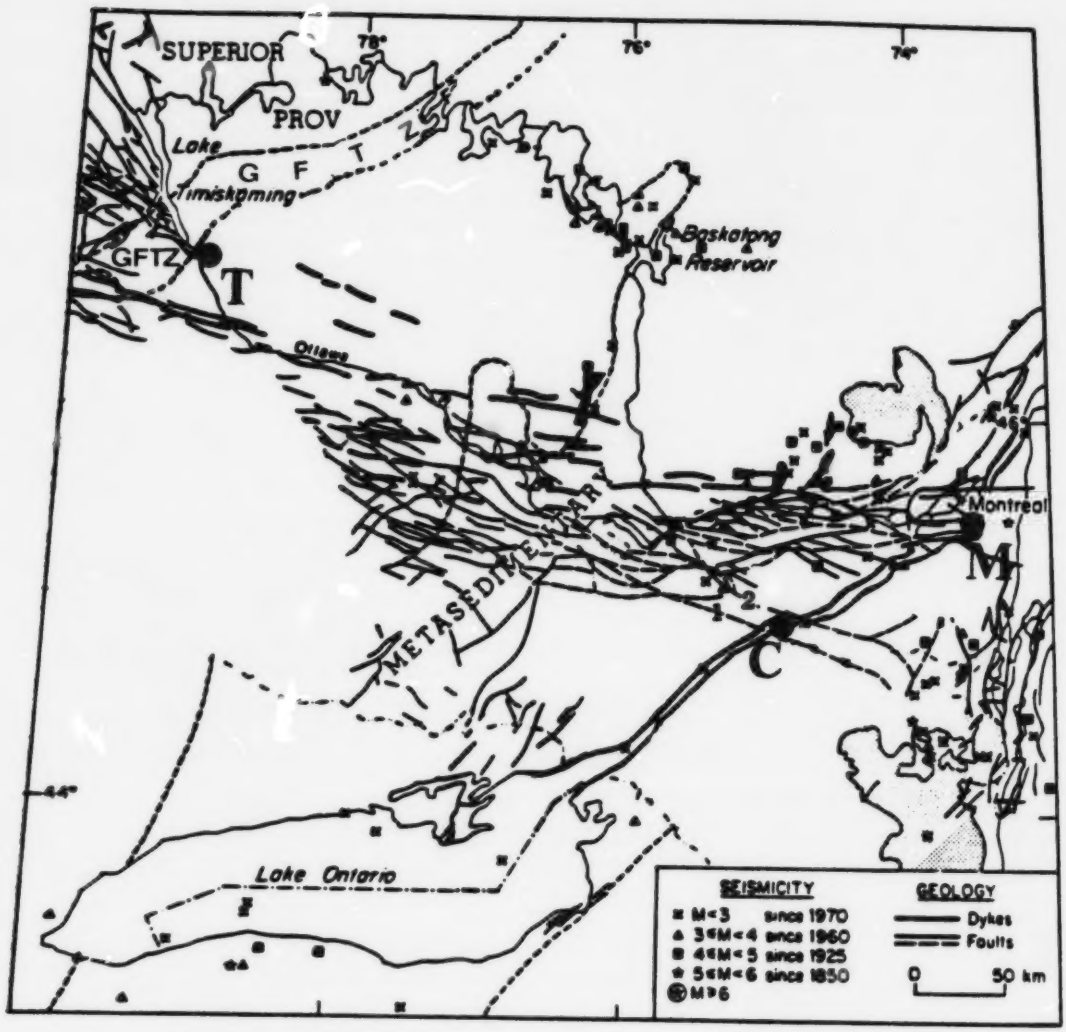
Figure 19. Examples of major North American earthquakes which have occurred at intersections of prominent linear features.

Upper figure shows the locations of the Montreal M (M=5.6-6.0), Cornwall C (M=5.9) and Timiskaming T (M=6.25) earthquakes. GFTZ is the Grenville Front Tectonic Zone.

(Modified after Forsyth, 1981)

Lower figure shows the location of the Grand Banks earthquake (M=7.2), which occurred in 1929.

(From Hasegawa and Kanemori, 1987)


SUPERIOR
PROV
Lake
Timiskaming
G F T Z
GFTZ
T
Baskatong
Reservoir
Ottawa
Montreal
M
METASEDIMENTARY
C
Lake Ontario
SEISMICITY
M<3 since 1970
3≤M<4 since 1960
4≤M<5 since 1925
5≤M<6 since 1850
M>6
GEOLOGY
Dykes
Faults
0 50 km

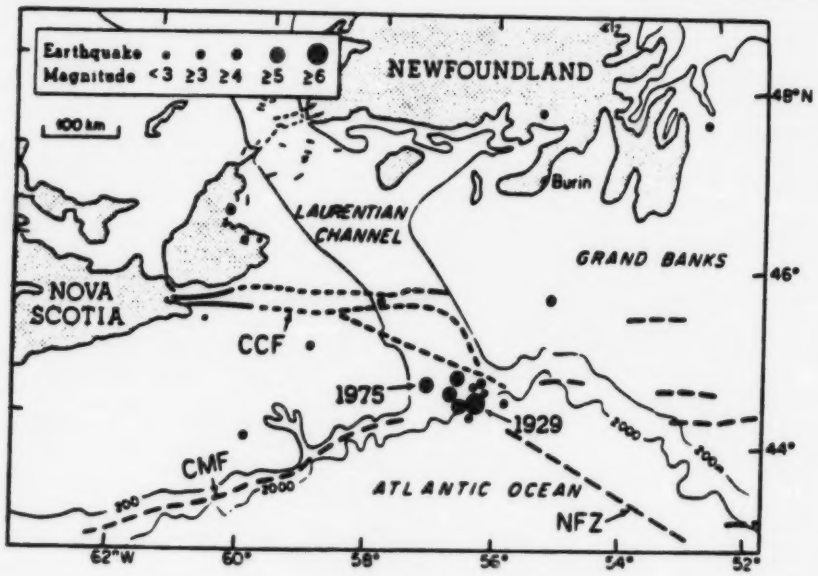
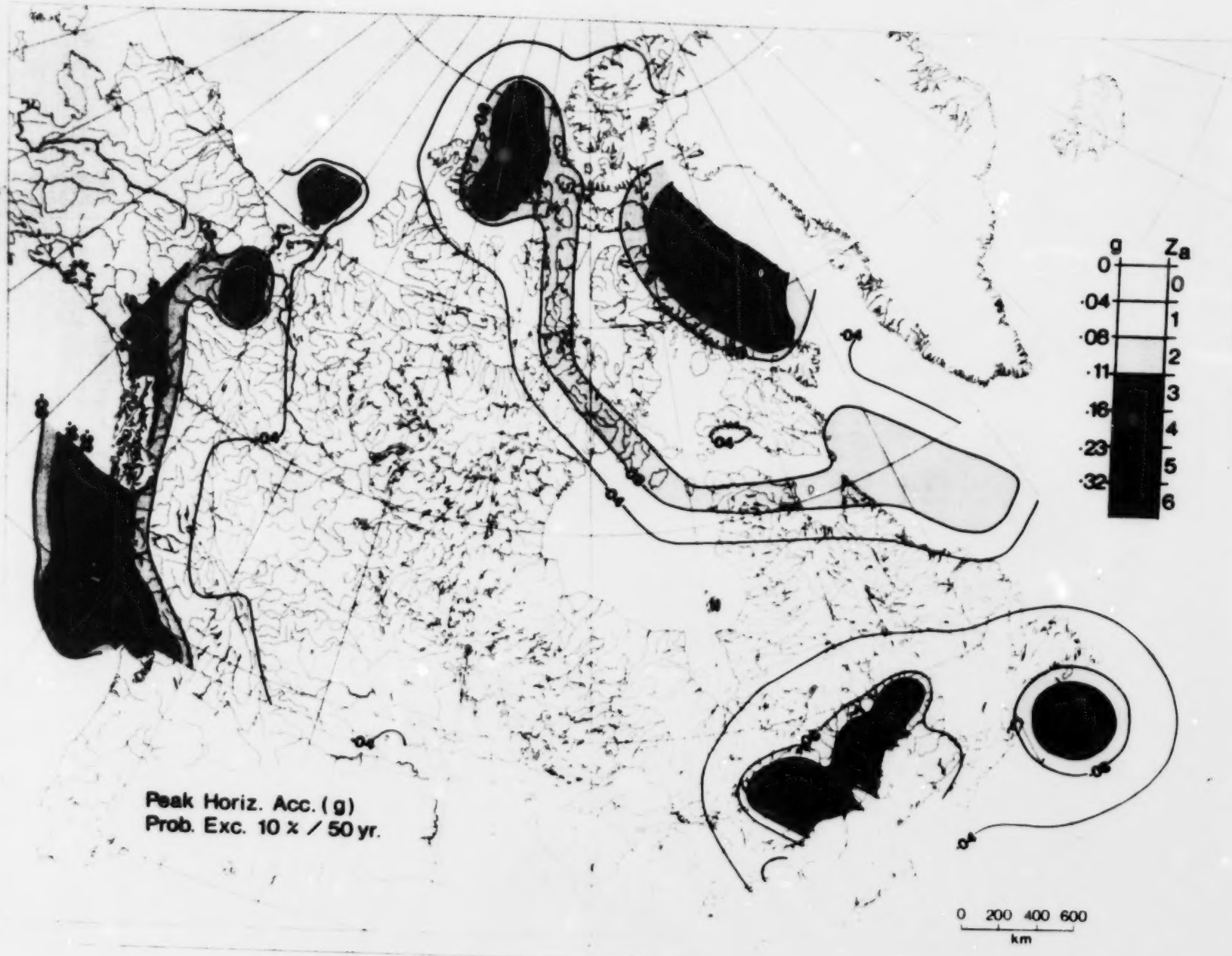

Earthquake
Magnitude <3 ≥3 ≥4 ≥5 ≥6
100 km
NEWFOUNDLAND
Burin
LAURENTIAN
CHANNEL
GRAND BANKS
NOVA
SCOTIA
CCF
1975
1929
CMF
ATLANTIC OCEAN
NFZ
48°N
46°
44°
62°W
60°
58°
56°
54°
52°

Figure 20. Seismic zoning map of Canada.

(From the Geological Survey of Canada)


g
Za
0
·04
·08
·11
·16
·23
·32
0
1
2
3
4
5
6
Peak Horiz. Acc. (g)
Prob. Exc. 10 % / 50 yr.
0 200 400 600
km

MAPS
NOT
FILMED

CARTES
OMISES